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Tectonic map of the Death Valley ground-water model area, Nevada and California

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Prepared in cooperation with the
Nevada Operations Office
National Nuclear Security Administration
U.S. Department of Energy
(Interagency Agreement DE-A108-96NV11967)

Pamphlet to accompany
Miscellaneous Field Studies Map MF-2381-B

2002

U.S. Department of the Interior
U.S. Geological Survey

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INTRODUCTION

The purpose of this map is to provide tectonic interpretations in the Death Valley ground-water model area to be incorporated into a transient ground-water flow model by the U.S. Geological Survey (D'Agnese, 2000; D'Agnese and Faunt, 1999; Faunt and others, 1999; and O'Brien and others, 1999). This work has been conducted in collaboration with the U.S. Department of Energy in order to assess regional ground-water flow near the Nevada Test Site (NTS) and the potential radioactive waste repository at Yucca Mountain. The map is centered on the NTS and its perimeter encircles the entire boundary of the numerical flow model area, covering a total area of 57,000 km^2.

This tectonic map is a derivative map of the geologic map of the Death Valley ground-water model, Nevada and California (Workman and others, 2002). Structures portrayed on the tectonic map were selected from the geologic map based upon several criteria including amount of offset on faults, regional significance of structures, fault juxtaposition of rocks with significantly different hydrologic properties, and the hydrologic properties of the structures themselves. Inferred buried structures in the basins were included on the map (blue and light blue dotted lines) based on interpretation of geophysical data (Ponce and others, 2001; Ponce and Blakely, 2001; Blakely and Ponce, 2001). In addition, various regional trends of fault zones have been delineated which are composed of multiple smaller scale features. In some cases, these structures are deeply buried and their location is based primarily on geophysical evidence. In all cases, these zones (shown as broad red and blue stippled bands on the map) are significant structures in the region. Finally, surface exposures of Precambrian crystalline rocks and igneous intrusions of various ages are highlighted (red and blue patterns) on the map; these rocks generally act as barriers to groundwater flow unless significantly fractured.

The following text is subdivided into a discussion of pre-Cenozoic tectonic features, characterized by repeated episodes of compression producing regional thrust faulting and arc magmatism, and Cenozoic tectonic features characterized by extensional normal and strike-slip structures and widespread caldera magmatism. Two stages of Cenozoic extension are discussed. The earlier stage, from Paleocene to Miocene, was dominated by calc-alkaline caldera magmatism and secondary faulting. The later stage, from Miocene to the present and here referred to as the basin-range episode, was dominated by normal and strike-slip faulting and secondary bimodal magmatism. There are significant variations in the topographic expression, character, and timing of late Cenozoic basin-range deformation across the region of the map, and three broadly defined physiographic subregions can be defined and are summarized below with respect to major structures within each subregion. They are (a) the southern Great Basin, characterized by the classically expressed north-trending basins and ranges in the northern and northeastern part of the map area; (b) the Walker Lane belt, a variably oriented and irregular set of ranges and basins adjoining the Nevada-California border in the northwestern, central, and southeastern areas; and (c) eastern California basin and range, an extremely rugged system of northwest to north-trending basins and ranges in the western and southwestern parts of the map (figure 1). The topography of these subregions mostly reflects variations in both structural style and rates of neotectonic

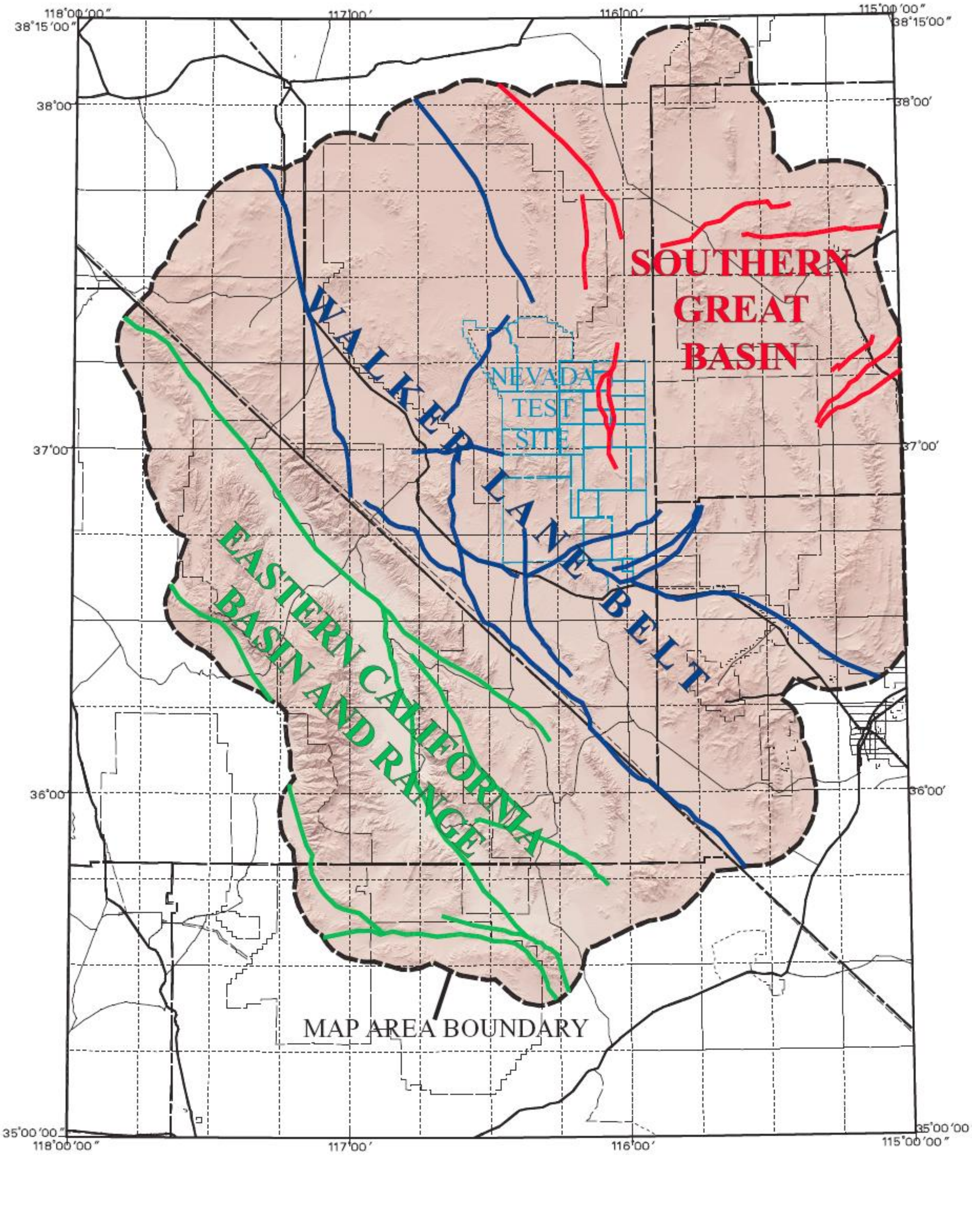


Figure 1: Three major Basin-Range extensional episode physiographic subregions discussed within the map area. Major structures grouped within each region are shown by colored solid lines.

deformation. Rocks involved in the structures, for the most part, will not be described. For detailed lithology descriptions, the reader is referred to the description of map units accompanying Workman and others (2002).

PRE-CENOZOIC TECTONIC STRUCTURES

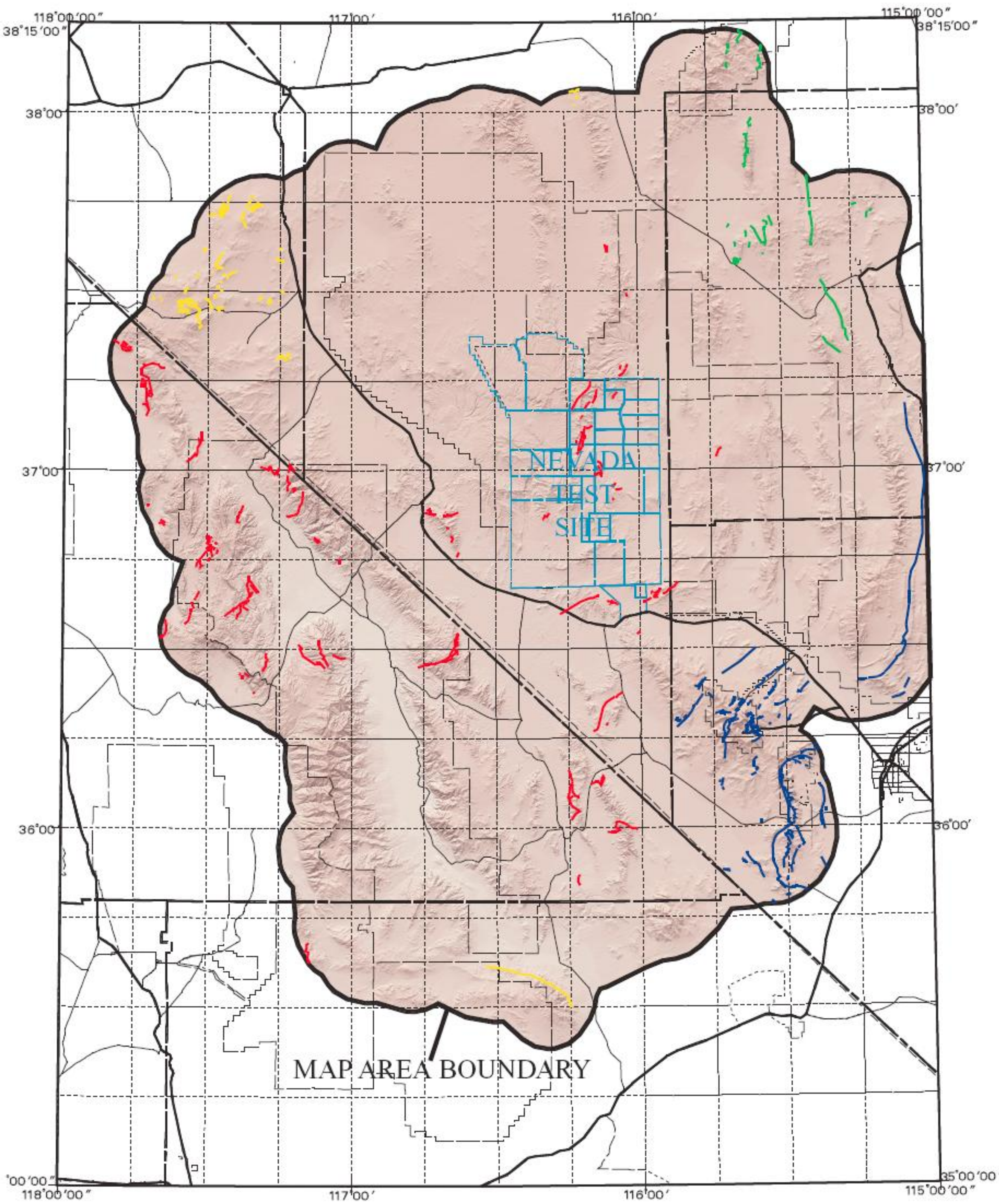
INTRODUCTION

Early Proterozoic tectonic history and associated structures are not discussed in this text because the ground-water model does not extend into Early Proterozoic rocks. Any structures confined to these units exist below the floor of the ground-water model and are therefore beyond the intended scope of this study.

Major recognizable post-Early Proterozoic structural activity in the area of the Death Valley ground-water model began with episodic uplift and probable thrust faulting during the Antler orogeny, starting in Late Devonian time with the highland persisting at least into Late Mississippian time (Kleinhampl and Ziony, 1985). Although no thrust faults of Antler age have been identified in this region, the effects of the orogeny are evidenced in the presence of coarse conglomerate and chert-rich sandstone and intercalated slide masses in the Eleana Formation on the NTS and equivalent age rocks in the Cactus Range. Other evidence for the Antler orogeny in the map area is the Ordovician Palmetto Formation in Esmeralda County. Rocks of the Palmetto Formation are eugeosynclinal and part of the western siliceous assemblage of rocks (Stewart and Carlson, 1978) which were interpreted as upper plate rocks of the Antler orogen (Albers and Stewart, 1972; McKee, 1985). Both upper and lower contacts of the formation are almost everywhere marked by a fault.

Uplift of the western part of the mapped area associated with arc magmetism may have occurred in Jurassic and Cretaceous time during the Nevadan orogeny. Sierra Nevada batholithic activity is reflected in numerous dioritic to granodioritic intrusive masses within the map area. According to Kleinhampl and Ziony (1985), folding and thrusting associated with the orogeny was directed southward and eastward in northern Nye County, but no thrusts of Nevadan age are known within the map area. The strata are, however, locally intensely folded.

Most exposed thrust faults in the map area correspond with the cordilleran fold and thrust belt of the western U.S. Three regional orogenic belts, the Death Valley thrust belt (Snow, 1992), Sevier orogenic belt (Armstrong, 1968; Fleck, 1970a), and the Central Nevada thrust belt (Taylor and others, 1993) exist within the map area (figure 2). Most of these thrusts were emplaced during the Mesozoic, but some may be as old as Permian. A majority of the thrusts are east-directed, and are shown on the map as isolated fault segments in widely separated ranges. Prior to Cenozoic extension, many of the thrusts were continuous structures across the region. Their current configuration across the map area resulted from movement along regional structures that laterally offset and rotated them during episodes of Cenozoic crustal extension and strike-slip movement. Isolated thrust fault segments within the three belts have been correlated and used as structural markers for paleogeographic reconstruction and estimating rates of extension across this part of the Basin and Range province (Wernicke, Axen, and Snow, 1988; Wernicke, Snow, and Walker, 1988; Snow and Wernicke, 1989; Snow, 1992). Correlations were based on stratigraphic throw, thrust vergence, and fault spacing and style. Individual thrust correlations are discussed below.



thrust faults associated with the Death Valley thrust belt

thrust faults associated with the Sevier orogenic belt

thrust faults associated with the central Nevada thrust belt

thrust faults in Esmeralda County and other locations associated with Tertiary extension

Figure 2: Distribution of the three major Mesozoic (to Permian?) orogenic thrust belts discussed in the text and younger thrust faults associated with Tertiary extension.

DEATH VALLEY THRUST BELT
(central, western, and southern sections of the map area)

Thrust faults in the central and western part of the map area are part of the Death Valley thrust belt (Snow, 1992). In the Death Valley area proper, these thrusts include from west to east, the Last Chance and Marble Canyon thrusts in the Cottonwood Mountains and Last Chance Range, and the Grapevine and Schwaub Peak thrusts in the Grapevine and Funeral Mountains, respectively. In the NTS area, they include the Meikeljohn and Panama thrusts at Bare Mountain, and the Belted Range, CP, Specter Range, and Spotted Range thrusts.

The Last Chance thrust (Stewart and others, 1966; Snow, 1992) juxtaposes Precambrian, Cambrian, and Ordovician rocks in the upper plate against Devonian to Permian rocks in the lower plate. The hanging wall ramp of the thrust is exposed in the southernmost Last Chance Range and is concealed along the west side of Dry Mountain. Klippen in the central Cottonwood Mountains were interpreted as part of the Last Chance allochthon (Stewart and others, 1966; Snow, 1992). Stewart and others (1966) originally mapped structural windows in the northern Last Chance Range, Saline Range, and Jackass Flats as part of the Last Chance thrust, but Corbett and others (1988) interpreted these thrusts to be part of a structurally higher Eureka thrust plate, based on dissimilar Paleozoic facies and isopachs in the two plates, and differences in structural style. Snow (1992) correlated the Last Chance thrust with known Permian-age thrusts in the Darwin Plateau region of southeastern California, west of the map area.

The Marble Canyon thrust, exposed in the eastern Cottonwood Mountains, is highly modified by Cenozoic normal faults, and is deformed by the Hunter Mountain pluton of Jurassic age. The Schwaub Peak thrust in the Funeral Mountains juxtaposes Proterozoic to Ordovician rocks in its upper plate against rocks as young as Permian in its lower plate. It has been correlated with the Marble Canyon thrust based on stratigraphic throw, structural position, and presence of footwall synclines (Snow, 1992). The Grapevine thrust in the northern Grapevine Mountains is correlative with the Last Chance thrust and juxtaposes Cambrian rocks in the upper plate against rocks as young as Permian in the lower plate.

The most recent summary of thrusts in the NTS area is that of Cole and Cashman (1999). The major thrust in the area is the east-directed Belted Range thrust, which juxtaposes rocks of Late Proterozoic age in the upper plate above Mississippian rocks in the lower plate with a stratigraphic throw on the fault of 7 km (Cole and Cashman, 1999). The Belted Range thrust is correlative with the Meikeljohn thrust at Bare Mountain, the Grapevine thrust in the Grapevine Mountains, and the Last Chance thrust (Cole and Cashman, 1999; Snow, 1992). At Bare Mountain, the southeast-directed Meikeljohn thrust juxtaposes Cambrian rocks in the upper plate against Devonian and Mississippian rocks in the lower plate, and the northwest-vergent Panama thrust juxtaposes mostly Late Proterozoic rocks in the upper plate against Lower Cambrian rocks in the lower plate.

East of the Belted Range thrust is the west-vergent CP thrust which juxtaposes Cambrian and Ordovician rocks in the upper plate against Mississippian to Permian rocks in the lower plate. At the map scale, the CP thrust is cut out by normal faults and is therefore not highlighted, but is labeled where it has been mapped at larger scales in the southern CP Hills, south of Yucca Flat. The thrust is part of a regional zone of west-directed structures also present in the Cottonwood Mountains, and at Bare Mountain. Monsen and others (1992) correlated the CP thrust with the Panama thrust at Bare Mountain. Potter and others (1998) interpreted the CP thrust as a backthrust that formed synchronously with the Belted Range thrust.

The Specter Range thrust (Burchfiel, 1965) juxtaposes Late Proterozoic and Cambrian rocks in its upper plate against Ordovician to Devonian rocks in its lower plate. It has been correlated with the Schwaub Peak thrust in the southern Funeral Mountains, and the Marble Canyon thrust in the southern Cottonwood Mountains (Cole and Cashman, 1999; Snow, 1992; Wright and Troxel, 1993)

The Spotted Range thrust juxtaposes Cambrian rocks in the upper plate against Devonian and Mississippian rocks in the lower plate. Snow (1992) correlated this thrust with the Specter Range thrust, but Cole and Cashman (1999) interpreted the two as separate faults.

Mesozoic thrust faults affect the Paleozoic rocks in the southeastern part of the mapped area. Burchfiel and others (1983) mapped and correlated several major thrusts that include, from north to south, the Montgomery thrust in the Montgomery Mountains, the Baxter and Resting Spring thrusts in the Resting Spring Range, and the Chicago Pass, Shaw, and Nopah Peak thrusts in the Nopah Range. Due to structural complexity, correlation of these thrusts with thrusts in the Sevier orogenic belt to the northeast and the Death Valley belt to the northwest is controversial. For example, Burchfiel and others (1983) and Wernicke, Snow, and Walker (1988) correlated the Chicago Pass and Shaw thrusts in the Nopah Range with the Wheeler Pass thrust in the Spring Mountains. Alternately, Snow (1992) correlated the Montgomery thrust with the Wheeler Pass thrust, and Abolins (1999) interpreted the equivalent to the Wheeler Pass thrust to be concealed in Pahrump Valley, or to be exposed in the Kingston Range.

The age of thrusts in the Death Valley belt is poorly constrained. Snow (1992) interpreted the Last Chance thrust system as Permian in age based on correlation of the thrust system with Permian thrusts in the Darwin Plateau region, and intrusion of the thrust plate by Triassic and Jurassic plutons. In the NTS area, Cole and Cashman (1999) reported that thrusts were post Early Permian and pre-Late Cretaceous.

SEVIER OROGENIC BELT
(eastern and southeastern sections of the map area)

Major thrusts in the Sevier orogenic belt (Armstrong, 1968; Fleck, 1970a) include the Wheeler Pass in the northwestern Spring Mountains, the correlative Gass Peak in the Las Vegas and Sheep Ranges, and the Keystone thrust in the eastern Spring Mountains. The Wheeler Pass thrust juxtaposes Late Proterozoic and Lower Cambrian clastic and carbonate units in its upper plate against mostly overturned Pennsylvanian and Permian units in its lower plate. Stratigraphic separation on the thrust is 4.8 km (Vincellette, 1964), and Fleck (1970a) estimated 7 km of lateral shortening. Equivalence of the Wheeler Pass and Gass Peak thrusts across the Miocene-age Las Vegas Valley shear zone is well established (Stewart, 1967; Page and others, in press; Wernicke, Axen, and Snow, 1988). The two thrusts have been used as structural markers across the shear zone on which estimates of 50 km of horizontal displacement are based (Burchfiel, 1965; Wernicke, Axen, and Snow, 1988; Wenicke, Snow, and Walker, 1988).

Like the Wheeler Pass, the Gass Peak thrust juxtaposes Late Proterozoic and Lower Cambrian clastic and carbonate units in its upper plate against Pennsylvanian and Permian rocks of the Bird Spring Formation in the lower plate. Guth (1981) reported the thrust to have as much as 5.9 km of stratigraphic displacement and greater than 30 km of horizontal displacement. The thrust can be traced from the Fossil Ridge area of the southern Las Vegas Range to the northernmost Sheep Range where the thrust abuts the Maynard Lake fault and becomes concealed by Tertiary volcanic rocks. The fault may correlate with the Mount Irish thrust of the Central Nevada thrust belt in the Timpahute Range (see below).

The Keystone thrust (Longwell, 1926) is the longest continuously exposed thrust in the entire map area and is the frontal thrust of the cordilleran fold and thrust belt. The thrust juxtaposes Cambrian carbonate rocks in its upper plate against upper Paleozoic and Mesozoic rocks in its lower plate. The Mesozoic lower plate rocks include terrigenous shale, claystone, and mudstone. The Pennsylvanian, Permian, and Triassic age lower plate rocks contain varying amounts of gypsum and anhydrite. The Keystone thrust correlates with the Muddy Mountain thrust exposed in the Muddy Mountains area, northeast of Las Vegas and east of the map area (Fleck, 1970a; Fleck and Carr, 1990; Wernicke, Snow, and Walker, 1988; Page and others, in press).

The age of thrusts in the Sevier orogenic belt is poorly constrained, but most workers agree the major episode of compression occurred during Cretaceous time (Fleck, 1970a). The age of the Keystone thrust is based mostly on radiometric dates of synorogenic deposits cut by the thrust. In the Goodsprings area of southern Nevada, for example, the Keystone thrust cuts deposits of the Lavinia Wash sequence (Carr, 1980; Fleck and Carr, 1990). Preliminary conventional K-Ar dates for the Lavinia Wash were Late Jurassic to Early Cretaceous (154+/-10 Ma) and thus established a maximum age for the thrust. New laser-fusion 40Ar/39Ar methods yielded dates of 99+/-.04 Ma for the sequence, establishing a further refined maximum age for the Keystone thrust as late Early Cretaceous (Fleck and Carr, 1990).

CENTRAL NEVADA THRUST BELT
(northeastern sections of the map area)

Thrusts of the Central Nevada thrust belt were described by Taylor and others (1993) and Tschanz and Pampeyan (1970). Most of the thrusts in the belt are outside the map area, but part of the belt extends into the Timpahute and Pahranagat ranges in the northeastern part of the map area. The Lincoln thrust is exposed in the western Timpahute Range and juxtaposes rocks of the Ordovician Pogonip Group against a complicated footwall consisting of a duplex zone of Ordovician, Devonian, and Mississippian rocks. Taylor and others (1993) estimated stratigraphic throw on the thrust of 3.2 km and lateral shortening of 3-4 km.

East of the Lincoln thrust is the Mount Irish thrust, which, like the Lincoln thrust, juxtaposes rocks of the Pogonip Group in the upper plate against Devonian and Missisippian rocks in the lower plate. Stratigraphic throw on the fault is about 3 km and minimum lateral shortening is 1.5 to 2 km (Taylor and others, 1993). The thrust correlates with the Golden Gate thrust (Tschanz and Pampeyan, 1970; Taylor and others, 1993) in the Golden Gate Range, north of the map area.

The East Pahranagat syncline (Jayko, 1990) is exposed south and east of the Mount Irish thrust. It is a gently north-plunging fold that has a steep to overturned west limb, indicating east-directed compression. In the hinge of the fold, rocks of the Mississippian Joana Limestone are thrust above rocks of the Mississippian Chainman Shale to form an out-of-syncline thrust. South of the Mount Irish Range, we believe the Mount Irish thrust is concealed by Tertiary volcanic rocks, and that the East Pahranagat syncline is most likely a lower plate structure and splay of the thrust in that area.

Correlation of thrusts in the Central Nevada and Sevier belts is unclear due to extensive cover by Tertiary volcanic rocks and complicated structure related to the Pahranagat shear zone within the intervening area. However, the Gass Peak thrust may correlate with the Mount Irish thrust. North of the Maynard Lake fault, upper plate rocks of the Pogonip Group in the Gass Peak thrust plate appear displaced westward across the fault, consistent with left-slip observed along the fault (Tschanz and Pampeyan, 1970). These rocks project northward along strike with rocks of the Pogonip Group in the upper plate of the Mount Irish thrust. North of the Maynard Lake fault, a continuous belt of Devonian and Mississippian rocks, deformed by the East Pahranagat syncline, likely forms the lower plate of the Gass Peak and Mount Irish thrusts. The Gass Peak loses throw northward along the east flank of the Sheep Range, which is consistent with the presence of older lower plate rocks (Devonian and Mississippian) northward in the Mount Irish area.

The minimum age of contraction in the part of the Central Nevada thrust belt that covers the map area is early Tertiary, based on the presence of Oligocene rocks which are the oldest rocks not involved in thrusting. For other thrusts in the belt, the maximum age is Late Permian, or more likely Jurassic (Taylor and others, 1993).

THRUST FAULTS IN ESMERALDA COUNTY, NEVADA
(northwestern sections of the map area)

Low-angle faults, referred to as thrusts by Albers and Stewart (1972), are common in the Palmetto Mountains and Montezuma Range of Esmeralda County, where they form nearly half of the pre-Tertiary rock contacts. Along most of these faults, younger rocks overlie older rocks although the more extensive faults have older over younger. These faults are recognized on the basis of the presence of structural discordance, and in places, attenuation of strata. It is unclear whether any of these faults are of regional scale, or are local gravitationally induced structures. Albers and Stewart (1972) believe most of these faults formed during oroflexural bending and intrusion of Middle Jurassic to early Tertiary plutons. In some cases these structures may actually be misidentified Tertiary detachment faults (J.H. Stewart, written communication, 2000).

CENOZOIC TECTONIC FEATURES

PRE-BASIN-RANGE EPISODE FEATURES

INTRODUCTION

Calc-alkaline magmatism in the map area began during early to middle Tertiary time and accommodated brittle, crustal extension resulting from rising asthenosphere and possible resteepening of the subduction zone along western North America (Burchfiel and others, 1992; Christiansen and Yeats, 1992; Lipman, 1992). Magmatism, characterized by shallow intrusion and caldera magmatism, occurred in belts that paralleled the subduction direction and were bounded on their northern or southern sides by transverse zones or lineaments. Such zones separated areas of different types, rates, or relative amounts of extension, and appear to have been extremely long lived, dating from the Cretaceous to the basin-range deformational episode in late Tertiary time (Ekren and others, 1976; Rowley, 1998).

Faulting accompanied the development of intrusions or formed independently of igneous centers but was secondary to magmatism during this early period of extension (Rowley, 1998). Most of these faults strike northeast or northwest (Ekren and others, 1968) with a strong component of left-lateral and right-lateral strike-slip deformation, respectively. The direction of principle maximum compressive stress for these faults was north to northeast.

The topography that resulted from this pre-basin-range faulting and magmatism was mostly obscured by the younger basin-range episode. Furthermore, this topography does not appear to have been characterized by high mountain ranges, as during the later basin-range deformation. In fact, most of the topography seems to have been subdued and caused by the calc-alkaline volcanism, which built stratovolcanoes and calderas. Most of the calderas outside the NTS in the mapped area formed during this episode.

EARLY CALDERA MAGMATISM

Mount Helen Caldera (northcentral section of the map area)

Mount Helen is a volcano that erupted a thick lava pile of intermediate composition and thin basalt dikes and flows much later. Deep erosion of the flanks of the mountain has revealed a northwest-striking graben bounded on the east by a metamorphic core complex (McKee, 1983) consisting of gneiss, schist, and thick quartz veins. The graben is bounded on the west by an uplifted block of conglomerate of pre-volcanic Tertiary age, which rests directly on lower Paleozoic rocks (Ekren and others, 1971). The graben is inferred to be part of a 14.5 km-wide, northwest-striking rift zone that includes the Cactus Range caldera on the north and the Black Mountain caldera and Timber Mountain caldera complex on the south.

Ekren and others (1971) inferred that, prior to the eruption of intermediate lavas, the Mount Helen caldera erupted two ash-flow tuff cooling units informally correlated with the lower tuffs of Antelope Springs. Mount Helen is located near the center of the known distribution of these tuffs. The two cooling units are about 500 m thick, and the base of the sequence is not exposed. The upper unit is directly overlain by alternating fluvial and lacustrine strata thereby indicating that a topographic low existed immediately after the eruption of these tuffs. Ekren and others (1971) suggested that this topographic low area might have resulted from caldera collapse prior to eruption of the intermediate lavas. Because there is no exposure of a topographic or structural wall for this caldera, the boundary shown on the tectonic map is speculative and based on outcrops of presumed intracaldera rocks. In the Cactus Range, the lower tuffs of Antelope Springs overlie the Monotony Tuff dated at 27.3 Ma (Best and others, 1989) and they underlie the upper tuffs of Antelope Springs that have been dated at 27.7-26.2 Ma (Ekren and others, 1971). Therefore, if the correlation of the two cooling units at Mount Helen with the lower tuffs of Antelope Springs is correct, then collapse of the Mount Helen caldera occurred at about 27 Ma.

Cactus Range Caldera (northcentral section of the map area)

The Catus Range was mapped by R. E Anderson and the following discussion is summarized from his description in Ekren and others (1971):

The Cactus Range is a large structural block about 29 km long and 8 km wide that is inferred to be the greatly uplifted infilling of a large caldera complex. The oldest Tertiary unit in the Cactus Range is the Monotony Tuff, which was deposited on a surface of moderate relief developed on gently-dipping upper Paleozoic rocks. The Monotony Tuff is overlain by ash-flow tuffs of the lower and middle parts of the tuff of Antelope Springs. During eruption of the upper tuff of Antelope Springs, caldera collapse occurred, as indicated by the contorted, sheared, and steeply tilted nature of the tuffs. Major collapse is especially documented in the northern part of the range, where as much as 245 m of mostly thin-bedded lacustrine rocks rest on the upper tuff of Antelope Springs. Partial resurgence within the inferred Antelope Springs caldera is suggested by deeply eroded, intensely deformed tuff of the Antelope Springs in the northern part of the range. The tuff of White Blotch Spring, derived from a source within or adjacent to the Cactus Range, unconformably covered the Cactus Range caldera complex.

Caldera subsidence appears to have occurred extensively along a northwest zone of the range block. Steep northeast tilting and local overturning of the tuff of White Blotch Spring and underlying rocks occurred in a zone as much as l.6 km wide and at least 13 km long on the north and west flanks of the range. Some areas of structural chaos exist within this zone. Considerable subsidence of the central part of the range is supported by intrusion of stocks, sills, and laccoliths into sedimentary rocks older than the tuff of White Blotch Spring. The thickness of this overburden must have been considerable because it contains laccoliths, and it also must have included large thicknesses of the tuff of White Blotch Spring, which are assumed to have been removed by erosion during later uplift of the range.

Following caldera subsidence, intense and prolonged intrusive activity continued, during which about 200 exposed intrusive masses were emplaced. These rocks range in composition from melanodiorite to high-silica rhyolite. Lavas and tuffs flanking the northern part of the range probably were erupted concomitantly with emplacement of some of the intrusive masses. During the latter part of this igneous activity, the range was uplifted to its present structural level. Uplift occurred along a system of faults that cross-cut the range. The uplift was sufficient that in places parts of what probably constituted the original floor of the complex have been brought to the present erosion level.

Quinn Canyon Range Caldera (northeastern section of the map area)

Recent studies by E. B. Ekren and P. D. Rowley (unpublished data, 1999, 2000, and 2001) show conclusively that the Quinn Canyon Range is a large caldera complex that gave rise to voluminous ash-flow tuffs and rhyolite lavas. As summarized by Sargent and Houser (1970), it is the source of the widespread Shingle Pass Tuff of Cook (1965). Best and others (1989) reported an age of 27-26 Ma for the Shingle Pass Tuff. The conclusion that the caldera is the source of the Shingle Pass Tuff is based on the occurance of "bottomless" sections of massive, densely welded tuffs of Shingle Pass affinity exposed within major horst blocks in the range. Additional mapping is necessary to define areas of collapse in the Quinn Canyon Range caldera complex that could be sources for the Shingle Pass Tuff. These intracaldera rocks have been intensely altered (sericitization, argillization, calcification, and replacement of feldspar by andularia). Silicification of these rocks is locally characterized by introduction of massive chalcedonic and crystalline quartz veins. The intensity of the alteration makes correlation of the intracaldera tuffs with outflow tuffs at the type locality of the Shingle Pass Tuff extremely difficult.

The Quinn Canyon Range has been dramatically faulted into several north trending horsts and grabens. The faults that formed these structures apparently cut through the calderas and any underlying magma chambers. The inferred volcanic structures certainly did not serve as competent bodies that resisted or deflected later basin-range normal faults. Although no topographic caldera boundaries are preserved, boundaries shown on the tectonic map are based on the inferences of Sargent and Houser (1970) and Best and others (1989). Areas of collapse perhaps defining the largest caldera of the complex are filled with a quartz-rich tuff correlated with a tuff in the Reveille Range that is also inferred to fill a deep caldera. This correlation indicates that the caldera in the Reveille Range may be part of the Quinn Canyon Range caldera complex and was separated by strike-slip and normal faults.

Bald Mountain Caldera (eastern section of the map area)

The core of the Bald Mountain caldera, within the Groom Range, was dramatically uplifted during the late Tertiary relative to the surrounding basins, so the caldera must have experienced deep subsidence to survive the resulting uplift and erosion of the range block. The intracaldera rocks presently stand topographically above the surrounding extracaldera rocks as a result of this uplift and the extracaldera rocks subsequently being stripped from the edges of the caldera margin. Despite this dramatic uplift, there is no upwarping of the intracaldera rocks to indicate resurgence (Ekren and others, 1977).

The rocks related to caldera eruption were informally named the tuff of Bald Mountain and determined to be about 25 Ma based upon regional stratigraphic relationships (Ekren and others, 1977). The tuff of Bald Mountain consists of two or more rhyolite ash-flow tuff cooling units with very similar phenocryst and lithic assemblages. Intercalated slide masses composed of Paleozoic rocks and intruded dikes and sills of porphyritic quartz latite to rhyodacite are common within the intracaldera assemblage. Hydrothermal alteration has removed most fresh phenocrysts, but the presense of sphene and its alteration products was used by Ekren and others (1977) to suggest correlation with exposures of similar tuffs in the Reveille Range, the Belted Range, the southern flank of the Quinn Canyon Range, and the south end of the Pancake Range (north of the map area), and within drill holes on Yucca Flat. They explain absence of correlative units east of Bald Mountain by pre-basin-range, left-lateral offset along the eastern range front fault of the Groom Range. This interpretation is supported by the presence of thick Paleocene conglomerates within the Jumbled Hills area, which are most likely offset left-laterally from the main mass of conglomerate in the Fallout Hills, west of the Pintwater Range.

Kawich Range Caldera (northern section of the map area)

The Kawich Range caldera complex in the northern part of the Kawich Range was first recognized as a resurgent caldera by E. B. Ekren, E. H. McKee, and C. L. Rogers (Stewart and Carlson, 1976). Thick intracaldera megabreccia is exposed at the extreme northern end of the range and a circular neck of vertically dipping welded tuff is exposed on the west flank of the range. The informal tuff of the Kawich Range caldera complex, consisting of at least two ash-flow cooling units, is the intracaldera facies of one or both of the lower and upper cooling units comprising the tuff of White Blotch Spring, as mapped by Ekren and others (1971) who identified the Cactus Range and the northern Kawich Range as two possible source areas. Best and others (1989, 1995) defined the Pahranagat Formation, which they correlated with the upper tuff of White Blotch Spring based upon paleomagnetic and age data, to be 22.39 Ma. They considered the thick tuff exposed in the Kawich Range and the southern Reveille Range to be intracaldera Pahranagat Formation, thereby making the source caldera very large, measuring 50 km in a northwest direction and 26 km in a northeast direction. Reconnaissance mapping by Gardner and others (1980) extended the northwest-striking Bellehelen lineament, exposed in the Kawich Range, across Reveille Valley to the southern termination of the Reveille Range and we have further extended this structure across the Reveille Range into the Monotony Valley (see discussion below). This structure could have a sizeable strike-slip component (Ekren and others, unpub. data, 1966) that could have pulled the Reveille Range segment from the Kawich Range.

Goldfield Caldera (northwestern section of the map area)

A graben, inferred to be related to caldera collapse, extends east from Goldfield and is well defined to the west and northwest by an arcuate normal fault. The dacite vitrophyre of Ransom (1909), a biotite-rich welded ash flow (21.1 Ma; Cornwall, 1972), extends south from the inferred southern boundary of the caldera and was most likely erupted during subsidence (Cornwall, 1972). Several north-trending, arcuate faults cross the western part of the graben and successively drop strata down to the east. There is no evidence of resurgence.

The dacite vitrophyre overlies the dacite (20.8-21.6 Ma; Silberman and McKee, 1972) of Ransome (1909) that hosts the majority of the gold and silver deposits in the Goldfield district. Chemical analyses actually indicate a rhyodacitic composition for both units and a close genetic relationship. The dacite, highly altered in all exposures, consists of intrusive rocks in Esmeralda County and flat-lying extrusive flows in Nye County (Albers and Stewart, 1972; Cornwall, 1972).

Cathedral Ridge Caldera (northcentral section of the map area)

The Cathedral Ridge caldera is the source of the widespread Fraction Tuff (Ekren and others, 1971). The 18- 17 Ma Fraction Tuff (Cornwall, 1972) is exposed from the Belted Range to the Tonopah area. The tuff reaches its maximum thickness of 2,200 meters at Trailor Ridge, on Cathedral Ridge, where Ekren and others (1971) described a single, densely welded compound cooling unit. The tuff contains a diagnostic assemblage of abundant lithic fragments that were incorporated during ascent through the crust that led to its original misidentification as a breccia in the Tonopah area by Spurr (1905).

Cathedral Ridge is cut by numerous northwest-striking normal faults that decrease in abundance northward. Two closely spaced faults have a combined offset of greater than 2,100 meters which Ekren and others (1971) interpreted as the southwestern boundary of the Cathedral Ridge caldera. The northern boundary of the caldera is obscured by younger structures. Uplift of a horst block in the southern Kawich Range after caldera subsidence is indicated by a thick sequence of fanglomerates that overlie the Fraction Tuff in exposures along the eastern and northern margins of Cathedral Ridge.

STRUCTURES

Timpahute Transverse Zone (northeastern section of the map area)

The Timpahute transverse zone is most dramatically defined by the east-west-trending Timpahute and Mount Irish Ranges that anomalously cut across the north-trending grain of basins and ranges in the region. The zone, like other transverse zones in the area, is not defined by any one mappable fault trace. Interruptions and alignments of aeromagnetic anomalies, east-striking strike-slip faults of varying offset, alignment of intrusive bodies, hot springs, and mineral deposits, and an apparent east-west-trending alignment of earthquake epicenters help to define this presumably deep-seated crustal structure (Ekren and others, 1976). The zone separates areas of contrasting structural style, stress configuration, and extensional magnitude from north to south and seems to have controlled the northern margin of the Caliente caldera complex to the east of the map area (Ekren and others, 1976, 1977; Rowley, 1998).

The age of this transverse zone is unclear, but it clearly predates the eruption of the Caliente caldera in early Miocene time. Scott and Swadley (1992) mapped lower Oligocene ash-flow units of the Needles Range Group ponded against north-facing scarps formed by the Pahroc Valley fault to the east of the map area which is an integral part of the Timpahute transverse zone in this area, indicating activity well into the Neogene. The truncation of both basin-range structure and topography against the zone indicates tectonic activity into the basin-range episode of extension. Seismic epicenters extending from Coal Valley to Dry Lake Valley east of the map area along the southern end of the North Pahroc Range indicate that the structure is still active today (Ekren and others, 1977).

We have highlighted some major, mapped structures within the transverse zone on the tectonic map, but it should be noted that this structure is interpreted as a broad, deeply buried crustal structure underlying this entire zone.

Bellehellen Lineament (northern section of the map area)

The Bellehellen lineament is a northwest-trending structure defined by Gardner and others (1980) as an exposed fault zone, the Bellehellen fault zone, which cuts through the northern end of the Kawich Range and extends into southern Reveille Valley. We have extended the southern terminous of this structure beyond the south end of the Reveille Range into Monotony Valley at the south end of Railroad Valley based upon interpretation of isostatic gravity gradients aligned with the structure and buried structure inferred by Ekren and others (1973). There is also an alignment of mineral deposits along this lineament.

The structure associated with this lineament seems to have offset rocks of the Kawich Range caldera, but Gardner and others (1980) imply that this fault zone is the surface expression of a deep-seated crustal structure which may have controlled the Kawich Range caldera and two other calderas to the north of the map area in the Monitor Range. This would suggest that this structure existed into the pre-basin-range period. Several basin-range age structures are offset and truncated by the lineament. There are no known Quaternary offsets, but it appears to control present basin topography and drainage which implies continued activity into the Quaternary.

BASIN-RANGE EPISODE FEATURES

INTRODUCTION

Sometime before 20 Ma, subduction ceased and the San Andreas transform fault placed much of the western United States in a giant torque, or wrench, resulting in oblique extension over a broad area known as the Basin and Range province (Hamilton and Myers, 1966). The Great Basin covers much of this province that is characterized by north-trending basins and ranges controlled by range front normal faults. The southern part of the Great Basin extends into the northeastern section of the map area.

Right-lateral shear transferred inland from the San Andreas system and in part accommodated the north-northwest translation of the Sierra Nevada block relative to the rest of the North American plate. This shear generated the Walker Lane belt, characterized by a long, broad belt of discontinuous and short-lived right-lateral faults and secondary normal faults defining pull-apart basins. The Walker Lane belt trends north-northwest separating the Great Basin from the Sierra Nevada block along the California-Nevada border and its southern end crosses the center of the map area from northwest to southeast.

A small zone at the southwestern edge of the Walker Lane belt, referred to as the Eastern California Basin and Range, marks the intersection of the Walker Lane belt with the relatively undeformed Mojave block as it deflects away from the southern end of the Sierra Nevada block. This region is characterized by concentrated right-lateral shear and dramatic extension within a series of classic rhombohedral pull-apart basins resulting from bends in the strike-slip system. Right-lateral faults within this region are more continuous, better defined, and longer lived and display greater slip rates than those in the Walker Lane belt and continue to be active today. This region covers the southwestern part of the map area.

During this period, magmatism was secondary to faulting as an expression of extension and was of bimodal composition—basaltic rocks and high-silica rhyolitic rocks. The rocks of the central Death Valley volcanic field and the southwest Nevada volcanic field and the calderas in the NTS constrain the age of this extensional episode.

SOUTHERN GREAT BASIN

Late Cenozoic extensional deformation within the southern Great Basin was dominated by movement along north- to northeast-striking normal faults related to development of the characteristic basin and range structure and associated topography. There is also some lateral slip deformation localized along east- to northeast-trending transverse fault zones (Rowley, 1998). Most of the large north-striking normal faults form the structural boundaries between the grabens or half-grabens beneath the basins and the horsts or tilted fault blocks of the ranges (Stewart, 1980), although locally there are many smaller intra-valley normal faults related to secondary internal structures of the basins as well. Many of these faults have been inactive since at least mid to late Quaternary time, and thus are buried beneath basin-fill and (or) surficial deposits along the basin margins. Although there is a general correspondence between these inactive faults and the topographic range fronts, the actual location and geometry of most of these structures are interpreted from geophysical surveys (Blakely and others, 1999). However, a number of the normal faults in this region are associated with fault scarps that displace upper Pliocene to Quaternary surficial deposits. Major range-bounding normal faults active in the Quaternary in this part of the region include: the Belted Range fault (see below), the Penoyer fault, possibly small sections of the Kawich and Tikaboo faults, the east Reveille Range, Hot Creek-Reiveille, and west Railroad faults, the Carpetbag and Yucca faults (see below), the west and east Pintwater Range faults, the Sheep Basin, Sheep Range, and Sheep-East Desert Range faults (Dohrenwend and others, 1991, 1992; Anderson and others, 1995a; Piety, 1996). There are also some small fault scarps in Cactus Flat and Emigrant Valley (Piety, 1996; Slate and Berry, 1999; Slate and others, 2000). The presence of fault scarps and persistent low-level historic seismicity also indicates activity on component faults within the Pahranagat shear zone as well (see below). Paleoseismic and tectonic geomorphic studies in the southern Great Basin subregion indicate moderate to low rates of neotectonic deformation on these faults characterized by slip rates in the 0.001- 0.01 mm/yr range and recurrence intervals between surface-rupturing events on the order of 104-105 years (Anderson and others, 1995a, b; dePolo, 1998).

Yucca and Carpetbag faults (central section of the map area)

The Carpetbag fault, and its companion to the east, the Yucca fault, are typical of intrabasin normal faults within the basin-range north of the Las Vegas Valley shear zone and the Walker Lane belt, and also north of the left-lateral faults of Rock Valley and nearby zones (Brocher and others, 1998). Both faults are significant because they have been broken by some of the many underground nuclear tests in Yucca Flat.

The Carpetbag fault is the major fault that controls Yucca Flat basin on the NTS. Recent geophysical studies by Phelps and others (1999) have determined that Yucca Flat basin consists of two main sub-basins separated by a gravity ridge, or horst block. The deeper sub-basin underlies the eastern half of Yucca Flat, where basin-fill deposits reach a maximum thickness of 2.5 km. A significant density boundary determined by gravity data exists along the west flank of this sub-basin, and corresponds with the Carpetbag fault zone. The Carpetbag fault lacks significant pre-testing surface expression, other than a possible short 1-km long scarp, although the fault does contain secondary carbonate fracture fillings that, on the basis of U-series ages, suggest multiple fracturing events with no significant displacements in the late to middle Pleistocene (Shroba and others, 1988).

The Yucca fault has an impressive surface expression, but based on gravity data, has comparatively small topographic expression beneath the Cenozoic basin-fill, which is interpreted to indicate minimal vertical offset within the basement rocks (Phelps and others, 1999). Associated with the Yucca fault is a prominent set of Quaternary fault scarps with maximum heights of 15 m that predate nuclear testing and displace Pleistocene alluvial deposits potentially as young as late Pleistocene (Swadley and Hoover, 1990; Dohrenwend and others, 1992).

Belted Range fault (northcentral section of the map area)

The Belted Range fault is a major west-dipping normal fault that forms the structural boundary between the Belted Range and Kawich Valley. Along most of its extent, the fault is buried by basin fill and (or) surficial deposits. However, a prominent set of west-facing fault scarps is developed in middle to upper Quaternary deposits along the southern end of the fault (Dohrenwend and others, 1992; Anderson and others, 1995a). Reconnaissance paleoseismic investigations of these fault scarps indicate (a) multiple surface-rupturing events on large composite scarps ranging from 2 to 15 m in height; (b) a most recent early Holocene event within an approximate 1 m surface offset; and (c) an estimated late Quaternary slip rate of 0.01-0.09 mm/yr, with the former more likely (Anderson and others, 1995a). This rate is similar in magnitude, albeit slightly lower, than a long-term estimate of slip rate on the fault of 0.05 mm/yr that is derived by a possible 600-m vertical displacement of a 12.5-11.5 Ma tuff across the fault (Ekren and others, 1971; Sawyer and others, 1994; Anderson and others, 1995a).

Pahranagat shear zone (eastern section of the map area)

The Pahranagat shear zone is a northeast-striking, left-lateral transfer fault zone at the northeastern margin of the map area that links and accommodates normal displacement on north-striking basin-range faults southeast and northwest of it (Liggett and Ehrenspeck, 1974; Ekren and others, 1977; Scott and others, 1990; Page and others, 1990; Swadley and Scott, 1990; Rowley, 1998). Tschanz and Pampeyan (1970) estimated approximately 9-16 km of cumulative, left-lateral displacement across the shear zone based on offset of the Hiko Tuff. Areas north and northwest of the shear zone were highly affected by Cenozoic extensional faulting in contrast to areas south of the shear zone in the southern Delamar Mountains to the east of the map area (Page, 1993).

The shear zone consists of three major faults. They are, from north to south, the Arrowhead, Buckhorn, and Maynard Lake faults (Jayko, 1990; Tschanz and Pampeyan, 1970). Ekren and others (1977) note that local basalt lavas are intercalated with the Hiko and Kane Wash Tuffs within the southern end of the Pahranagat Valley in the vicinity of the shear zone which thin and decrease in abundance to the southeast and northwest. The shear zone most likely acted as a conduit for these Miocene basaltic flows. Eakin (1966) describes a major groundwater level gradient in the Paleozoic rocks across the Maynard Lake fault which he explains as a thick section of volcanic rocks on the northern side of the fault that act as a barrier or dam to southward moving groundwater in the regional carbonate aquifer.

Scarps indicative of Quaternary displacements have been reported on several strands of the fault zone (Ekren and others, 1977; Schell, 1981; Piety, 1996), and the zone has been the locus of persistent low-level (M 3-4) instrumentally recorded seismicity that is a major element of the east-trending Southern Nevada seismic belt in the southern Great Basin (Rogers and others, 1991).

THE WALKER LANE BELT

The Walker Lane belt, as redefined by Stewart (1988) and Stewart and Crowell (1992) from the earlier concepts of Giannella and Callaghan (1934) and Locke and others (1940), is a 700-km-long, northwest- to north-northwest-trending belt of valleys and ranges along the Nevada-California border that are dominated by strike-slip faults. As originally defined based on combined Mesozoic-Cenozoic tectonic characteristics, the Walker Lane belt is a complex structural zone that separates the Sierra Nevada on the west from areas of typical basin-range topography to the east (Stewart, 1988; Stewart and Crowell, 1992). Within the map area, the Walker Lane belt is separated from the southern end of the Sierra Nevada structural block by the eastern California basin and range which is considered a separate tectonic province as discussed below.

Deformation in the Walker Lane belt is complex and includes a variety of intricately related structures. Within the map area are several large subregional-scale right-lateral fault zones with dominant northwest orientations, but the region also contains a number of other coeval structures, including east-northeast-trending left-lateral strike-slip faults and north- to northeast-trending normal faults. Regional westward-verging detachment faults and metamorphic core complexes that are younger westward are abundant in the Walker Lane belt (McKee, 1983; Hamilton, 1988; Wright and Troxel, 1993; Wernicke, 1992). The Walker Lane belt structures are discontinuous and appear to complexly interact with one another in accommodating an overall mixed right-shear and extensional strain field in the region. This complex fault network is also reflected in regional patterns of historical seismicity recorded since 1950 at the NTS. Microearthquake focal mechanisms indicate spatially intermixed slip on a network of dextral, sinistral, and normal slip on fault sets with north, east-northeast, and northeast trends, respectively; this kinematic pattern is consistent with a west-northwest-oriented regional least compressive stress (Rogers and others, 1987).

Oroflexural bending is another locally important tectonic element in the Walker Lane belt. Ranges and structures within and adjacent to the Las Vegas Valley shear zone and within the Silver Peak-Palmetto Mountain area are locally dragged in a right-lateral sense within spectacular oroflexures. Although some of the oroflexural bending within the Silver Peak-Palmetto-Montezuma zone possibly is as old as Mesozoic (Albers, 1967; Albers and Stewart, 1972), Stewart and Crowell (1992) interpret deformation in the belt as most likely influenced by northwest-directed right-lateral shear that formed after about

20 Ma. Right-lateral offset of 32 km was estimated for the northern part of the Walker Lane belt and 48-60 km for the central part (Stewart and Crowell, 1992).

On the basis of a regional synthesis of data, Stewart (1988) suggested that strike-slip and normal faulting in the Walker Lane belt began about 26-25 Ma and continued to at least 15 Ma (John and others, 1989; John and Hudson, 1990; Hardyman and Oldow, 1991; Dilles and Gans, 1995). Dilles and Gans (1995) further suggested that the main phase of movement occurred at 14-12.5 Ma. Along the Walker Lane's eastern boundary, and in the southwestern NTS, the bulk of movement occurred at 13-7 Ma where considerable movement along faults in the Beatty area postdates the 11.6-11.45 Ma tuffs of the Timber Mountain Group (Fridrich and others, 1999a, b). Neotectonic activity is indicated on a small subset of the faults in the region by their association with fault scarps displacing Quaternary surficial deposits (Dohrenwend and others, 1991, 1992; Anderson and others, 1995a, b; Piety, 1996). Trench and scarp-based paleoseismic investigations indicate generally low to moderate slip rates and long recurrence intervals in the same range (0.001-0.01 mm/yr and 104-105 yrs, respectively) as those cited above for the Great Basin area to the northeast (Anderson and others, 1995a, b; dePolo, 1998; Menges and others, 1997, 1998), with the exception of higher composite slip rates of 0.1 mm/yr and 103- 104 yrs estimated for the Rock Valley fault system.

Eastern Limit of Walker Lane belt (northern section of the map area)

We show the eastern boundary of the Walker Lane belt as a northwest-striking fault zone that separates the Kawich Range and Cathedral Ridge from the Mellon Hills west of them. Deformation within the Mellon Hills follows the general characteristics of Walker Lane style of deformation but a north-northwest-trending normal fault defines the range front along the western side of the Kawich Range block which we conclude is characteristic of southern Great Basin structure. There is a distinct change in the trend of isostatic gravity anomalies from north-south to northwest-southeast orientations across this zone and truncation of gravity ridges that supports this conclusion (Ponce and others, 2001).

This fault zone on the west side of the Kawich Range strikes southeast into Pahute Mesa, where extension was taken up by a batholith from which the Silent Canyon caldera complex formed. Caldera magmatism and shallow intrusion is an integral part of Walker Lane deformation, but is also characteristic of the southern Great Basin extension, so the location of the boundary between these two subregions in the southwest Nevada volcanic field region is unclear. In fact, the boundary may be characterized by a zone of overlapping structural style of these two subregions.

Sarcobatus Flat-Goldfield Hills fault zone (northwestern section of the map area)

We informally name the structure within the map area previously defined as the Walker Lane by Locke and others (1940) as the Sarcobatus Flat-Goldfield Hills fault zone. Stewart and Crowell (1992) defined the Walker Lane belt as a broad zone of structures with the previously defined Walker Lane being the eastern structure within this zone. We extend the eastern boundary of the belt farther to the east (see above). Albers and Stewart (1972) mapped a fault extending from the northeastern edge of Lone Mountain across the eastern side of the alkali flat northwest of Goldfield. They continue the structure directly beneath the town of Goldfield and south, along State Highway 95, into northern Sarcobatus Flat. Locke and others (1940) described this structure as a right-lateral shear zone and implied that it continued to the southeast and joined with the Las Vegas Valley shear zone. Recent detailed mapping and geophysical studies (Langenheim and others, 1997, 1998, in press) show that the Las Vegas Valley shear zone truncates against the Rock Valley fault zone and does not extend farther north. We extend the structure mapped by Albers and Stewart (1972) south along the western edge of Sarcobatus Flat and across the western edge of the Bullfrog Hills to terminate against the Grapevine Mountains.

Within Sarcobatus Flat, Blakely and Ponce (2001) define two distinct north- to northwest-trending basins with depths of about 4 km that display en echelon right-stepping relationships. This may be a concealed right step over in the fault zone, but further studies are necessary to clarify this basin structure. No deep basins are associated with the fault zone through the Goldfield Hills region where it is largely concealed beneath younger volcanic units. To the north of the map area, in Big Smokey Valley, the northern segment of the structure follows a narrow (approximately 10 km wide), elongate basin parallel to the fault zone. This basin, as defined by gravity data (Blakely and Ponce, 2001) varies from 3 km deep in the southern end to only 1 km deep in the northern end where it intersects the east-striking, left-lateral Coaldale fault in the Warm Springs-Monitor Range transverse zone (Ekren and others, 1976; Rowley, 1998).

There is no surface exposure of this structure within the map area. The Miocene Thirsty Canyon (9.4-9.15 Ma; Slate and others, 2000) and Timber Mountain (11.6-11.45 Ma; Slate and others, 2000) volcanic units cross the structure with no offset, so it is inferred that this structure has not been active since middle Miocene time. In the Goldfield area, the fault zone passes near the western boundary of the Goldfield caldera, so it may have had some influence on caldera subsidence during the early Miocene, pre-basin-range time. The regional-scale oroflexure in the Silver Peak, Palmetto Mountains, and Montezuma Range bends into this structure north of the Goldfield Hills area. Albers (1967) argued that this oroflexure was caused by dextral drag in the upper crust, which at some depth is thought to have moved freely over deeper crust or the mantle. He considered that movements associated with the oroflexure possibly started as early as late Early Jurassic and were mostly completed by early or middle Miocene.

Thirsty Canyon lineament (central section of the map area)

The Thirsty Canyon lineament strikes northeast and extends from the northwestern corner of the NTS southwestward into Oasis Valley. The lineament is not exposed at the surface but is buried by younger rocks, notably volcanic rocks of the Thirsty Canyon Group (9.4-9.15 Ma). The lineament was first identified on the basis of gravity and aeromagnetic data (Grauch and others, 1997), and it was interpreted to be a buried fault zone. Additional geophysical studies (Hildenbrand and others, 1999; Mankinen and others, 1999; Schenkel and others, 1999) have refined the structure's location as shown by Slate and others (2000), who interpreted the zone as a fault zone one or more kilometers wide. Geophysical methods, however, failed to define the southwestern end of the lineament, so it is not shown extending southwest of the southern side of Thirsty Canyon (Slate and others, 2000). Because its location coincides with the western side of gravity lows interpreted as comprising the western boundaries of the Silent Canyon (at least as old as 13.7 Ma) and Timber Mountain (11.6-11.45 Ma) caldera complexes, the lineament is interpreted to have controlled and bounded the western sides of these two caldera complexes. This northeast-striking fault zone may be part of the pre-basin-range, high-angle, northeast-striking set described by Ekren and others (1968) as middle Tertiary (about 27-18 Ma). The lineament has seen significant activity in the time of basin-range extension however, so it may be a reactivated older structure.

Beatty Wash transverse zone (central section of the map area)

A broad (several kilometers or more) east-striking fault zone, herein named the Beatty Wash transverse zone, was identified on the basis of geophysics as marking or controlling the southern side of Oasis Valley (Grauch and others, 1997). From there, it extends eastward along the southern side of the Timber Mountain area. Gravity, aeromagnetic, and electrical studies (Hildebrand and others, 1999; Mankinen and others, 1999; Schenkel and others, 1999) helped to define the structure as a transverse zone, in the sense of Rowley (1998), separating areas of different styles of extension (Slate and others, 2000). North of this zone, shallow intrusions and major calderas dominate, whereas south of it major faults dominate. Northerly striking faults both north and south of the zone tend to terminate against it. Fridrich and others (1999a) suggested that the zone formed the southwestern side of the Rainier Mesa caldera (11.6 Ma) and remained active until at least 9.9 Ma. The transverse zone may be as old as middle or even early Tertiary.

Bare Mountain fault (central section of the map area)

The Bare Mountain fault is a major north-trending, east-dipping normal fault that forms the structural boundary between the eastern front of Bare Mountain and the western margin of Crater Flat (Monsen and others, 1992). The fault is discontinuously exposed along the base of Bare Mountain's faceted range front. The seismic reflection survey of Brocher and others (1998) clearly images this structure as a moderately east dipping (40-50°) normal fault bounding the west-tilted Crater Flat half-graben. The half graben is filled primarily with a west-dipping sequence of Tertiary and Quaternary basin-fill deposits (about 4 km deep) that overlies Tertiary volcanic rocks. Gravity modeling suggests the fault extends southward into the north-central Amargosa Desert (Blakely and others, 1998, 1999), where it may form the western boundary of the Amargosa trough of Blakely and others (1998).

Quaternary activity is indicated along a 20-km-long section of the northern Bare Mountain fault by a discontinuous set of fault scarps and its topographic position along the range front in Crater Flat. Trenching investigations by Anderson and Klinger (in press) indicate one to two surface rupturing events in late to middle Pleistocene time, suggesting slip rates and recurrence intervals on the order of 0.01 mm/yr and 104-105 yrs (100-200 ka), respectively. There is no evidence for Quaternary activity on the buried southern continuation of the fault in the Amargosa Desert.

Highway 95 fault (central section of the map area)

Fridrich and others (1996) identified the truncation of volcanic rocks at the southern edge of Crater Flat and Yucca Mountain based on magnetic studies and supported by drill-hole data from the Amargosa Desert. Slate and others (2000) show a concealed fault as following State Highway 95 at the southern end of Crater Flat. Based on gravity data (Blakely and others, 1999; Ponce and others, 2001), we interpret the fault, informally referred to as the Highway 95 fault, to extend eastward along the southern end of Jackass Flats and to truncate against the north-trending Gravity fault at the western end of the Specter Range. B. Slemmons (Fridrich, 1999a) proposed that the Carrera fault, which defines the southwestern boundary of the Bare Mountain block, is a right-lateral structure that extends eastward along the southern end of Crater Flat. We interpret the Carrera fault, however, to be truncated against the north-trending Bare Mountain fault, and the structure defining the southern end of Crater Flat and Yucca Mountain as a separate fault. An alternative interpretation of the gravity data is that this feature is simply a buried erosional scarp with no structural offset. Additional work is necessary to fully define this inferred feature.

Gravity fault (central section of the map area)

The Gravity fault (Winograd and Thordarson, 1975) is a prominent west-dipping normal fault concealed beneath basin-fill deposits in Jackass Flats and the northern Amargosa Desert. The fault is defined by seismic reflection (Brocher and others, 1993), gravity (Blakely and others, 1998, 1999), and aeromagnetic (Blakely and others, 1999) data and its location is supported by the presence of shallow Paleozoic basement in the footwall of the fault as identified from boreholes. The fault forms the eastern margin of the Amargosa trough of Blakely and others (1998), and, therefore, is structurally related to the central Amargosa part of the Pahrump-Stewart Valley-Central Amargosa fault system.

The fault is not well expressed at the surface. Aside from geophysical surveys, its position can only be inferred from the general westward limit of bedrock hills in the east-central Amargosa Desert. Donovan (1991) and Anderson and others (1995b) identified a 30-km-long zone of discontinuous lineaments and subdued small scarps (0.2-3.5 m high) developed in Pliocene and Quaternary surficial deposits which they termed the Ash Meadows fault zone. This diffuse zone of scarps approximately overlies the southern trace of the Gravity fault, as inferred in the subsurface from geophysics, between the western extent of the Skeleton Hills and the northern Resting Spring Ranges. These Ash Meadow fault scarps suggest a low level of Quaternary activity on at least this part of the Gravity fault, with an estimated late Pleistocene age for the most recent rupture and probable low slip rates of 0.01 mm/yr and long recurrence intervals of at least 15-50 ky (Anderson and others, 1995b).

Rock Valley fault zone (central section of the map area)

The east-northeast-striking Rock Valley fault zone (RVFZ) is the major left-lateral fault zone in the southern NTS area with a maximum length of 70 km. At its southwestern end it is truncated by the Gravity fault in the Amargosa Desert. To the northeast its strike changes to north and we interpret the fault to merge with the Buried Hills range front normal fault. This pattern is consistent with the oroflexural bending of mountain ranges north of the Las Vegas Valley shear zone which terminates at the RVFZ in Mercury Valley. Several other northeast- to east-striking left-lateral faults, including the Cane Springs, Mine Mountain, and Mid Valley faults exist to the north of the RVFZ. O'Leary (2000) suggested that the RVFZ is a boundary separating weakly extended, nonvolcanic rocks of the Spring Mountains-Specter Range domain to the south, from volcanic terranes to the north.

The RVFZ was active as early as about 29 Ma (Oligocene) according to O'Leary (2000). Fault scarps in mid-Pleistocene to Holocene surficial deposits indicate significant amounts of Quaternary deformation along the entire mapped length of the RVFZ (Yount and others, 1987; Anderson and others, 1995b; J.A. Coe, written communication, 2001). Trenching investigations in Rock Valley and Frenchman Flat indicate two surface ruptures, with a composite slip rate of 0.1 mm/yr for displacements summed across all strands and an average recurrence interval of 23 ka (J.A. Coe, written communication, 2001). Active seismicity has been recorded on this fault by Southern Nevada seismic network (Rogers and others, 1987; Smith and Brune, in press; Smith and others, in press a, b). The 1992 Little Skull Mountain earthquake (M5.8) was an oblique-normal-slip event centered immediately north of the RVFZ itself at 9-km depth on a northeast-striking buried fault not observed at the surface (Smith and others, in press a, b). A swarm of very shallow small magnitude (<3.5) left-slip earthquakes occurred on the Rock Valley fault in 1993, which likely were triggered by the Little Skull main shock (Smith and others, in press a, b). Both displacement per event and length parameters indicate the potential for a major surface-rupturing earthquake of M7.0-7.3 (J.A. Coe, written communication, 2001).

The Cane Spring fault to the north of the RVFZ is about 8 km long and follows the same strike as the RVFZ. It has been considered as possibly active in the Quaternary based on association with photointerpretive lineaments (Reheis and Noller, 1991). However, Quaternary activity could not be confirmed on the ground along this or other northeast-trending faults north of the Rock Valley fault, except for possible middle Quaternary displacements on a small section of the Mine Mountain fault southeast of Shoshone Mountain (O'Leary, 2000).

Mercury Valley fault zone (central section of the map area)

Within the Spotted Range are a series of northeast-trending oblique slip faults with a left-lateral, down to the north sense of offset (Barnes and others, 1982). These structures appear to be oroflexurally bent north of the Las Vegas Valley shear zone (LVVSZ) and become more northerly striking with a smaller component of strike-slip offset to the northeast based on correlation with structures in the northern Spotted Range and Ranger Mountains (Guth, 1990; Workman and others, 2002; Guth and Yount, unpublished mapping, 1994). Guth (1990) described these faults as reactivated portions of the Mesozoic Spotted Range thrust system. We consider these structures to be conjugate faults to the LVVSZ as suggested by Barnes and others (1982). This conclusion is supported by the apparent mutual offsets between the two structures as defined by gravity modeling within Mercury Valley (Slate and others, 2000; Ponce and others, 2000, 2001).

Barnes and others (1982) suggested that the strand of the Mercury Valley fault zone along the north edge of Crossgrain Valley in the Spotted Range may extend across Mercury Valley and the LVVSZ to the Specter Range. This interpretation is based on correlation of Mesozoic structures in the two ranges which is supported by Snow (1992). Interpretation of gravity data (Ponce and others, 2000, 2001), however, implies that the fault in the Spotted Range is truncated against a buried fault north of the main strand of the LVVSZ that in turn truncates the fault in the Specter Range. These two northwest-trending structures define a small graben paralleling the shear zone within Mercury Valley. The fault within the Spotted Range along the southern edge of the Mercury klippe of Barnes and others (1982) appears to offset the LVVSZ by more than 3 km as mapped by Slate and others (2000). These cross-cutting relationships support the interpretation of the Mercury Valley fault zone as a conjugate system to the LVVSZ and that deformation was contemporaneous in the two systems. There is no known indication of Quaternary offset along the Mercury Valley fault zone.

Las Vegas Valley shear zone (eastern section of the map area)

The Las Vegas Valley shear zone (LVVSZ) (Burchfiel, 1965; Campagna and Aydin, 1994; Dubendorfer and Black, 1992; Fleck, 1970b; Langenheim and others, 1997; 1998, in press; Longwell, 1974; Longwell and others, 1965; Lyles and Hess, 1988; Stewart, 1967; Stewart and others, 1968; Stewart and Crowell, 1992), striking west-northwest through the southeastern part of the mapped area, is characterized by as much as 23-69 km of right-lateral slip. The shear zone extends more than 100 km from Frenchman Mountain, on the east side of Las Vegas Valley, north-westward to terminate at the Rock Valley fault zone. Langenheim and others (1997, 1998, in press) described the shear zone as complex, and consisting of several continuous to discontinuous strands with associated steep-sided pull-apart sub-basins. They identified a major strand of the LVVSZ that marks the northern margin of Las Vegas basin along the southern Sheep and Las Vegas ranges. The Las Vegas basin is several kilometers deep at its northern end against this strand of the shear zone and at least 3 km deep on its eastern side on the west flank of Frenchman Mountain. A narrow, deep (>2 km) basin north of Corn Creek Springs is also interpreted as a pull-apart basin within the shear zone.

The LVVSZ is bounded by the Great Basin subprovince on the north and the southern Basin and Range subprovince on the south and accommodates different types and amounts of extension across these two subprovinces (Fleck, 1970b; Anderson, 1973; Liggett and Childs, 1977; Guth, 1981; Bohannon, 1984; Faulds and others, 1990; Duebendorfer and Black, 1992; Rowley, 1998). Ranges, faults, folds, and bedding north and south of the shear zone were oroflexurally bent into the fault zone in a right-lateral sense that Albers (1967) originally identified as a defining characteristic of the Walker Lane. It is unclear how the LVVSZ relates to the main trend of the Walker Lane belt since it is separated and displaced from the belt by younger, regional left-lateral structures. We include it in the discussion of the Walker Lane belt due to its similar style and timing of deformation. The principal faulting within the shear zone appears to have taken place between 14 and 8.5 Ma (Duebendorfer and Black, 1992). The shear zone is not associated with fault scarps or microseismicity indicative of neotectonic activity, but youthful (late Tertiary and Quaternary) fault scarps are evident south of the shear zone in Las Vegas Valley (Bell, 1981; Langenheim and others, in press; Page and others, in press).

Pahrump-Stewart Valley-Central Amargosa fault system (southcentral section of the map area)

The Pahrump-Stewart Valley-Central Amargosa fault system, also referred to by Blakely and others (1998) as the State Line fault system, is an extensive northwest-striking, right-lateral strike-slip fault zone that follows the Nevada-California State line. The fault also has been referred to as the Pahrump Valley fault zone (Wright and others, 1981; Hoffard, 1991), Amargosa River fault zone (Donovan, 1991), and the Amargosa fault zone (Schweickert and Lahren, 1997). Topographic expression of the zone extends nearly 175 km northwest from Ivanpah Valley through Mesquite Valley and Ash Meadows, and may continue northwestward to define the northeastern flank of the Funeral Mountains (Blakely and others, 1998). Based on gravity data, the bedrock basement concealed beneath alluvial valleys along the fault zone is structurally complex and consists of a series of narrow and steep-sided sub-basins interpreted by Wright (1987) and Blakely and others (1998) as transtensional, pull-apart basins, caused by en-echelon right steps during strike-slip faulting.

In Pahrump Valley, the basement or bedrock surface is relatively flat along the basin margins, but within the central part of the valley, two steep-sided basins are separated by a basement gravity ridge which parallels the northwest trend of the fault zone. The depth of the southwestern basin is 2 km, and the northeastern basin is nearly 5 km deep. The gravity ridge is exposed on the surface as a gravel-capped ridge that trends northwest through the Mound Spring and Stump Spring 7.5-minute quadrangles (Lundstrom and others, in press). Lundstrom and others (in press) and Blakely and others (1998) interpreted the ridge as a horst block uplifted by local compression between major reverse faults of the fault system resulting from transpression along left steps in the overall dextral system.

The fault system in the Amargosa Desert area is characterized by a deep trough that extends south from the southwest Nevada volcanic field to the Nevada-California State line. The trough is deepest beneath the southern end of the volcanic field. Depths of 7 km were estimated based on geophysics (Blakely and others, 1998). In the Devil's Hole-Ash Meadows area, the trough is generally less than 3.5 km deep, and like the Pahrump area, a basement gravity ridge separates two sub-basins, and is on strike with the Pahrump gravity ridge, suggesting continuity between the two geographically separated areas along the fault zone.

The geophysical expression of the overall fault zone across the region implies a major continuous subregional strike-slip fault during at least the major late Tertiary deformational interval of basin formation. However, this geophysically defined regional fault trace is not expressed at the surface, and indeed sections of the overall fault zone defined by the geophysical surveys cross range divides between the structural and physiographic basins developed along the structure. The presence of fault scarps along sections of the structure indicate Quaternary activity along parts of the overall fault zone (for example, southwest Pahrump Valley, Stewart Valley, and the Amargosa River fault zone; see Donovan, 1991; Hoffard, 1991; Anderson and others, 1995b; Blakely and others, 1998, 1999; Page and others, in press). These scarps are typically discontinuous and vary greatly in height (< 1 m to 15 m). Estimated recency of movement also varies across the structure from probable Holocene in the Pahrump and Stewart Valley areas to late Pleistocene in the Amargosa Desert (Donovan, 1991; Hoffard, 1991; Anderson and others, 1995b). Quaternary slip rates and recurrence intervals are very poorly constrained along any component of the overall zone, although Anderson and others (1995b) suggest a possible range of 0.009 to 0.02 mm/yr for the vertical slip component of the strike-slip fault in the Pahrump valley, based on 15 m scarps in sediments with estimated ages of

Pliocene to early Pleistocene. Recently acquired luminescence dating of these sediments in the 400-275 ka range (Page and others, in press) suggest slightly higher mid-late Quaternary vertical slip rates of 0.03-0.05 mm/yr. These combined data suggest that Quaternary surface rupturing has occured at varying times and relatively low to moderate rates along several components of the zone and large ruptures probably do not propagate during single earthquake events along the entire extent of the overall geophysically defined structural zone.

As with the Las Vegas Valley shear zone, it is unclear how the Pahrump-Stewart Valley-Central Amargosa fault system relates to the main trend of the Walker Lane belt. We include it in the discussion of the Walker Lane belt due to its similar style and timing of deformation, but it is more likely a transitional structure between the Walker Lane belt and the eastern California basin and range.

EASTERN CALIFORNIA BASIN AND RANGE

The eastern California basin and range is defined as the area of high-relief ranges and basins north of the Garlock fault between Death Valley and Fish Lake Valleys on the east and the Sierra Nevada on the west. This region is characterized by a prominent system of north-northeast to north-northwest-striking normal to oblique-normal faults and large, regional northwest-oriented right-lateral strike-slip faults (Jennings, 1994). Many of these structures are linked geometrically and kinematically within rhombic pull-apart basins (Burchfiel and Stewart, 1966; Burchfiel and others, 1987; Blakely and others, 1999). In some areas the overall oblique extensional strain field appears to be partitioned into coeval slip on discrete, commonly adjacent, sets of normal and strike-slip faults (Wesnousky and Jones, 1994). These faults accommodate very high rates and amounts of neotectonic deformation, responsible for producing the greatest local relief in the conterminous United States, that are one to several orders of magnitude higher than areas to the east of Death Valley. Typical slip rates on individual faults are on the order of 0.1 to >1 mm/yr, possibly exceeding 5mm/yr locally, with recurrence intervals ranging from 103 to 102 yrs (for example, Klinger and Piety, 1996; Zhang and others, 1990; Knott, 1998; Klinger, 1999).

A regional series of north- to northeast-trending normal faults have developed in the block between the two major northwest-trending zones of major strike-slip deformation within the map area. Collectively these faults appear to perform two tectonic functions. First, they accommodate additional secondary extension and fragmentation of the crustal block between the adjoining regional deformation zones in Death Valley and Panamint and Saline Valleys. This extension is manifested both as intramontane valleys and second-order basins. Secondly, the geodetically based tectonic model of Dixon and others (1995) for the eastern California shear zone predicts that these north-striking normal faults transfer and focus some of the regional right-lateral slip northward from the Panamint Valley-Hunter Mountain-Inyo fault system onto the Death Valley-Furnace Creek fault system and eventually onto the Fish Lake Valley fault.

The contemporary tectonic regime of this area developed after 6 to 4 Ma, and is the most recent extension within the region. The stratigraphy and structures associated with earlier episodes of extension, possibly beginning as early as Oligocene time as described by Snow and Lux (1999) in the Cottonwood Mountains, are exposed primarily within the range blocks and along the margins of basins, where they commonly are truncated by the currently active structures that define the present basin-range systems. Deformation commonly involves low-angle normal faults with either listric or detachment geometries. In many cases this extensional deformation is associated with prominent strike-slip faulting (Wright and Troxel, 1973, 1984, 1993; Hamilton, 1988; Fridrich, 1999b; Wernicke, 1999; Wright and others, 1999; Cichanski, 2000).

Dokka and Travis (1990) defined the eastern California shear zone as a diffuse zone of right-lateral shear that accommodates a significant component of plate motion inboard of the San Andreas transform boundary. They continued the eastern California shear zone northward from the active strike-slip faults of the central Mojave Desert through the eastern California basin and range on the basis of evidence for significant right-lateral slip displacement (as much as 6-12 mm/yr) on the composite set of faults in this region. Significant right-lateral slip compatible with this general interpretation has been observed on the major fault systems in the region by precise satellite-based geodetic measurements (Dixon and others, 1995; Reheis and Dixon, 1996; Bennett and others, 1997).

Death Valley-Furnace Creek fault system (western, central, and southern sections of the map area)

The Death Valley-Furnace Creek fault system is a 200-km-long set of linked right-lateral strike-slip and normal faults that structurally control the neotectonic evolution of the full length of Death Valley from the Avawatz Mountains north to the Last Chance Range (Brogan and others, 1991; Jennings, 1994; Klinger and Piety, 1996). The system comprises three major component faults that dominate the structure of the valley, including from south to north, the southern Death Valley fault zone, the Death Valley fault zone proper in the central part of the valley, and the Furnace Creek fault zone which includes the northern Death Valley fault. These structures are discussed in detail below. The Fish Lake Valley fault zone continues on strike to the northwest of the Furnace Creek fault zone beyond the map area at the northern end of Death Valley proper, and thus is considered a northwest continuation of the latter fault by some workers (Brogan and others, 1991); however, recent paleoseismic studies indicate seismotectonic behavior that appears to differ from the Furnace Creek fault to the southeast.

Secondary transpressive deformation, commonly manifested as elongate ridges of uplifted and warped basin sediments and surficial deposits, exist along the major strike-slip faults at the northern and southern ends of Death Valley. Blakely and others (1999) also postulate that most of the narrow deep subbasins in the basin interior defined by gravity modeling probably represent secondary intermediate-scale rhombic pull-apart structures, related to oblique extension or transtension on the major faults, that mimic the pull-apart geometry of the overall Death Valley fault system.

Complex deformation between Beatty Junction and Furnace Creek Ranch and continuing to the east along lower Furnace Creek Wash is probably related to slip transfer in this area between the Furnace Creek fault and the Death Valley fault. Structures in this transition zone include north-trending normal-slip fault splays at the southern terminus of the active strand of Furnace Creek fault, northwest-oriented synclines and anticlines in lower Furnace Creek Wash and Salt Spring Hills, related flexural-slip thrusts on the limbs of these folds, and northeast-trending normal faults that crosscut the northwest structures (Hunt and Mabey, 1966; Klinger and Piety, 1996; Klinger, 1999; Machette and others, 1999). Deformation on these active structures affects not only upper Tertiary sediments of the Furnace Creek and Funeral Formations, but also overlying middle to late Quaternary surficial deposits. These structures also appear to localize the distribution of the major spring discharge in at least the shallow subsurface of central Death Valley.

Southern Death Valley fault—The southern Death Valley fault is a 50-km-long northwest-striking primarily right-lateral fault that occupies the axis of southern Death Valley from north of the Avawatz Mountains to Shoreline Butte. The fault zone is complex and locally wide, with evidence for locally significant vertical as well as lateral displacements, including secondary transpressive deformation between adjacent strands (Butler and others, 1988; Klinger, 1999). There is abundant stratigraphic and geomorphic evidence for significant recurrent Pliocene to Quaternary displacements along its entire length, although key paleoseismic parameters are not well determined (Klinger, 1999). The most recent event is estimated as late Holocene, with mixed lateral and vertical slip components of 1.2 and 1.8 m, respectively. The late Quaternary slip rate is poorly constrained overall to less than 1 mm/yr, with the best estimate of 0.3 mm/yr derived from the 215 m of right-lateral offset of a cinder cone with a reported age of 0.69 Ma (Klinger, 1999).

Death Valley fault zone—The central Death Valley fault zone is a 60-km-long, north-northwest-trending primarily normal fault zone that forms the primary structural boundary between the eastern margin of central Death Valley and the base of the western range front of the Black Mountains from south of Mormon Point to north of Furnace Creek (Brogan and others, 1991; Klinger and Piety, 1996; Knott, 1998). The fault dips steeply west at the surface and both seismic reflection profiles and gravity modeling suggest steep to moderate dips in the subsurface (Serpa, 1990; Blakely and others, 1999). This fault is the master bounding structure controlling the eastward-directed subsidence and rotation of the central Death Valley half-graben. Slip on this fault is predominantly normal, but the possible presence of a lateral-slip component is more controversial. Klinger and Piety (1996) report only dip-slip on young fault scarps near Mormon Point, whereas Slemmons and Brogan (1999) present theoretical arguments and geomorphic data for a significant, Quaternary right-lateral slip on the fault.

The fault zone lies at the base of the turtleback surfaces prominently exposed along the western Black Mountains. These antiformal, low-angle normal-slip faults are generally interpreted to have primarily developed during Tertiary extension (Miller, 1999a). There is some controversy regarding the relationship of the structures to Quaternary activity on Death Valley fault at the range front. Both coeval movements on all of the structures and truncation of earlier turtleback surfaces by younger range-front high-angle faults have been proposed (Keener and others, 1993; Burchfiel and others, 1995; Knott and others, 1999; Miller, 1999b, Cichanski, 2000).

There is abundant evidence for Quaternary activity along the Death Valley fault both from the tectonic geomorphology of the range front (for example, steep linear mountain front, narrow incised wineglass canyons, vertical knickpoints in the channels of most canyons) and associated fault scarps that displace by varying amounts all Pleistocene and Holocene surficial deposits except for recent channel and fan deposits.

The age of the most recent event is not well constrained, but is certainly latest Holocene, and possibly < 1 ka, based on the presence of a small scarp with a vertical free face along most of the fault (Klinger and Piety, 1996; Klinger, 1999; Frankel and Jayko, 2000). Paleoseismic parameters are not well determined, with best estimates of 2.5 m for the vertical displacement per event, 1,000 to 2,000 yr for Holocene recurrence intervals, and approximately 1.5 mm/yr for the late Quaternary slip rate (Klinger, 1999; Knott, 1998).

A discontinuous set of fault scarps displace mostly upper to middle Pleistocene deposits of the large dissected alluvial fans on the western margin of central Death Valley (Hunt and Mabey, 1966; Brogan and others, 1991; Jennings, 1994). These scarps are typically short (commonly 0.5-2 km, and rarely as much as 5 km, in length) and commonly develop in subparallel clusters on the proximal, medial, and even distal parts of the fans. There is evidence for recurrent displacements on the faults, but probably at rates significantly lower than associated with the Death Valley fault zone to the east. A continuous, highly active basin-bounding fault trace is conspicuously absent along the eastern base of the Panamint Range. The observed pattern of faulting probably reflects secondary antithetic adjustments during the east-directed tilting and subsidence of the asymmetric half-graben against the master boundary fault on the east side of Death Valley.

Furnace Creek fault zone—The Furnace Creek fault zone is a major northwest-striking right-lateral strike-slip fault that continues for about 145 km from at least the southeast end of the Funeral Mountains in west-central Amargosa Desert and Furnace Creek Wash northwest along the axis of northern Death Valley to its junction with the Fish Lake Valley fault zone in the bedrock constriction of Cucomungo Canyon (Brogan and others, 1991; Jennings, 1994). The overall 105-km-long trace of the fault in northern Death Valley is associated with a nearly continuous series of geomorphic features indicative of recurrent lateral slip throughout the Quaternary, including variably facing scarps, aligned truncation of surficial deposits, laterally offset streams and fan surfaces, local shutterridges, and vegetation lineaments (Brogan and others, 1991; Klinger and Piety, 1996; Klinger, 1999). The fault also controls the major active seeps and discharge points at Grapevine, Sand, and Little Sand Springs at the northern end of the valley (Moring, 1986). The overall structural geometry of this part of the fault trace is simple and linear, with few large bends or step-overs that might segment surface ruptures during a major earthquake (Klinger and Piety, 1996; Klinger, 1999). There is significant uplift, locally associated with anticlinal warps and secondary thrust faults, near the southern and northern ends of this fault trace. However, there is no evidence of mid-late Quaternary activity on the southeastern section of the fault to the east of Death Valley proper, where the fault forms the structural boundary of the southern Funeral Mountains in Furnace Creek Wash and the central Amargosa Desert. This segment of the fault zone is discussed in more detail below in association with the Grandview and Sheephead faults, which are discussed in the following section. Gravity surveys indicate the presence of a very deep, narrow fault-bounded subbasin, with estimated maximum depths to basement of 5-7 km, beneath Mesquite Flats immediately southwest of the main fault trace (Blakely and others, 1999).

Estimates of total cumulative right-lateral offset of bedrock features across the fault vary from 40 to 128 km, but most likely are close to 65 to 80 km (Stewart, 1967; Stewart and others, 1968; Snow and Wernicke, 1988). Klinger (1999) cites additional estimates of cumulative right-lateral displacements for progressively younger Quaternary features, including 4 km for sediments containing the Bishop Tuff (0.76 Ma age), 250-330 m for a late Pleistocene fan surface, and 12 m for a late Holocene stream channel. These offset data suggest high Quaternary slip rates between 3 and 9 mm/yr, with a best estimate of 5 +/- 2 mm/yr. The geomorphic and soil-stratigraphic analyses of the segment in northern Death Valley by Klinger and Piety (1996) and Klinger (1999) provide additional estimates of 2-4 m for average lateral displacements (maximum of 6 m) during individual late Quaternary ruptures, an age of < 1,000 yr BP (possibly 300-400 yr BP) for the most recent surface rupture on the north end, and poorly constrained late Quaternary recurrence intervals of 700 to 1,300 yr.

A discontinuous series of short normal fault scarps exists along and proximal to the eastern and western mountain fronts to either side of the Furnace Creek fault in northern Death Valley (Brogan and others, 1991; Jennings, 1994). This activity probably represents secondary down dropping of the basin, contemporaneous with the primary lateral slip along the valley axis, that is markedly reduced relative to the major basin subsidence in central Death Valley to the south.

Grandview and Sheephead Faults (southcentral section of the map area)

Several large northwest-trending strike-slip fault systems have been identified in basins and ranges to the east of central Death Valley. These include the southeastern section of the Furnace Creek fault in Furnace Creek Wash and the west-central Amargosa Desert, the Grandview fault mainly in upper Furnace Creek Wash and Greenwater Valley, and the Sheephead fault in the southern Black Mountains and Sperry-Alexander Hills (McAllister, 1970; Wright and others, 1999; Wright, 1999; Cemen and others, 1999). These faults are intricately linked with middle Miocene through Pliocene deformational intervals, including extension, strike-slip faulting, basin formation, sedimentation, and volcanism that predates neotectonic formation of Death Valley proper to the west. These deformational intervals are recorded in the Artist Drive Formation, Furnace Creek Formation, Funeral Formation, the Greenwater Volcanics, volcanic rocks in the Resting Spring Range, and isolated sedimentary packages at Eagle Mountain, the southeastern Funeral Mountains, the northwestern Resting Spring Mountains, and the China Ranch and Dumont Hills basins (Cemen and others, 1999; Prave and McMackin, 1999; Snow and Lux, 1999; Wright, 1999; Wright and others, 1999).

The older strike-slip faults collectively are arranged in a general rhombic pattern that resembles the overall pull-apart geometry of the Death Valley fault system to the west. The strike-slip faults strongly influence the deformational and sedimentation patterns of the Tertiary basins. The southeastern Furnace Creek fault bounds and structurally controls the pull-apart basin containing the Artist Drive and Furnace Creek Formations exposed in upper Furnace Creek Wash, and the oblique offset Grandview fault splays off to the south from this structure and interacts with other normal faults in this basin in the Billie Mine area (McAllister, 1970; Wright and others, 1999). The inception of faulting on the proto-Furnace Creek fault in this area has been interpreted variously between 17 Ma (Cemen and others, 1999) and 10 Ma (Snow and Lux, 1999; C. Fridrich, oral communication, 2000). Deformation continued on these structures into the Pliocene depositional interval of the Funeral Formation, but ceased by at least middle to late Quaternary time, as indicated by the absence of scarps or other deformational features in surficial deposits of this age that overlie the southeastern Furnace Creek and Grandview faults in upper Furnace Creek Wash and northern Greenwater Valley (McAllister, 1970; Klinger and Piety, 1996; Workman and others, 2002). The much larger estimates for lateral offsets of bedrock versus Quaternary features in northern Death Valley suggest significant late Quaternary slip.

To the south, the Grandview fault merges into the west-northwest-trending Sheephead fault. This structure is truncated to the west by the easternmost fault of the Jubilee Basin of Wright (1999) formerly called the Jubilee phase of the Amargosa chaos by Noble (1941). Topping (1993) proposed that the granite breccias of the Jubilee Basin were in fact proximal deposits to the Kingston Peak intrusive body that were translated 30 km northwest along detachment faults which segmented this basin into the Jubilee, China Ranch, and Dumont Hills Basins and that these basins all formed prior to 7.8 Ma. However, Wright and others (1991) define all movement on the Amargosa detachment fault occurring before 10 Ma, eliminating the possibility of the younger Jubilee Basin being segmented from basins to the southeast. Prave and McMackin (1999) show that the depositional patterns of the China Ranch and Dumont Hills Basins are markedly different from the asymmetric pattern of the Shadow Valley Basin to the southeast that is characteristic of a detachment system. The segmentation of these genetically linked basins is explained by right-lateral displacement on the Sheephead fault. The easternmost end of the Sheephead fault zone is unclear as it projects into the detachment-dominated terrain of the Kingston Peak-Halloran Hills region.

Panamint Valley-Hunter Mountain-Inyo fault system (western and southern sections of the map area)

Panamint and Saline Valleys are structurally controlled by a set of geometrically and kinematically linked normal, normal-oblique, and strike-slip faults similar in some aspects to the Death Valley fault system. The major fault elements in this 160-km-long system are the Panamint Valley fault zone, the Hunter Mountain fault, and the Inyo fault zone (Jennings, 1994). Although not directly linked to this fault system, another major range-front fault controls east-directed subsidence in Eureka Valley to the north along the western flank of the Last Chance Range (Dohrenwend and others, 1992; C.M. Menges, and B. Turrin, unpublished mapping, 1983). There are also numerous secondary zones of faulting associated with this system. These include the Ash Hill fault zone in west-central Panamint Valley, near the base of the Argus Range, a set of north-trending scarps and grabens near the eastern margin of Saline Valley, and a swarm of short north-northwest-trending fault scarps and lineaments developed in playa and salt-pan deposits within the center of Saline Valley. All of these fault zones are marked by fault scarps in surficial deposits within the basins indicative of late Quaternary, and, in most cases, Holocene activity (Zellmer, 1980; Jennings, 1994; Densmore and Anderson, 1997; Oswald, 1998).

These basins and causative faults are only partly contained within the map area along its western margin, but are discussed in detail because they generate much of the local relief along the range crests that define the western model boundary.

Panamint Valley fault zone—The Panamint Valley fault zone is a 100-km-long, generally north-striking fault zone that forms the structural boundary between the eastern margin of Panamint Valley and the western flank of the Panamint Range. In detail, the fault trace displays a broadly curving sigmoidal shape characterized by a short north-trending central section and two longer north-northwest-oriented sections at either end of the zone. There is abundant evidence for not only normal-slip but significant and locally dominant right-lateral slip components on at least the northern and southern sections (Smith, 1979; Zhang and others, 1990). Burchfiel and others (1987) consider the northern section of this fault zone to be a low-angle detachment fault, an interpretation supported by the presence of exhumed turtleback-type normal fault surfaces elsewhere along the Panamint range front (Cichanski, 2000). A detachment geometry is also consistent with the broad shallow subsurface geometry of the Panamint Valley basin, which does not exceed depths of 500 m at the northern end, based on the gravity modeling of Blakely and others (1999). However, Cichanski (2000) reports that the range-front detachment surfaces are cut by a younger set of steeply dipping scarps associated with Quaternary activity on the range-bounding Panamint Valley fault. He interprets this relation as representing recent overprint by high-angle structures upon a basin system predominantly generated by a low-angle normal fault. There is abundant evidence for recurrent Quaternary activity along most of the Panamint Valley fault in the form of fault scarps varying in height from 6 to 61 m located at and basinward of the range front, including the large Wildrose graben (Smith, 1979; Zhang and others, 1990; Jennings, 1994). Smith (1979) estimates an average late Quaternary recurrence rate of 700-2500 yrs. Zhang and others (1990) use laterally offset landforms to derive a late Quaternary slip rate of 2.4 +/- 0.8 mm/yr for right-slip component on the southern end of the fault.

Hunter Mountain fault zone—The Hunter Mountain fault is a 45-km-long northwest-trending high-angle fault with mixed right-lateral and normal-slip (Zellmer, 1980; Burchfiel and others, 1987; Oswald, 1998). The fault geometrically links the northern end of the Panamint Valley fault with the southern end of Inyo fault, which is the primary range front structure along western Saline Valley. The Hunter Mountain fault appears to kinematically transfer the oblique extension between these two oppositely directed subsiding basins within a classic pull-apart system. This includes a significant right-lateral slip component along the length of the fault zone, estimated as high as 8-10 km of cumulative dextral offset since 3 Ma (Burchfiel and others, 1987). The fault also accommodates a major scissors-like normal slip component that increases in amount towards either end (north side down on the northwest and south side down on the southeast), from a pivot point at the bedrock divide near Hunter Mountain between each basin system (McAllister, 1956). Both Zellmer (1980) and Oswald (1998) document abundant geomorphic evidence in the form of fault scarps and laterally offset landforms for recurrent late Quaternary activity with both lateral and vertical slip components along the entire length of the fault zone. Geomorphic and soil-stratigraphic analyses by Oswald (1998) indicate a probable late(?) Holocene age for the most recent event along the fault, with vertical offset of 1 m and dextral offset of 1-2 m. He estimates large late Quaternary slip rates ranging from 1.6 to 4.0 mm/yr, compatible with the 2.6 mm/yr average slip estimate of Burchfiel and others (1987), and also derives potential recurrence intervals from both geologic and seismic data that vary between 570 and 1,870 yrs, with a preferred range of 600 to 850 yrs derived from slip rates of 2.6 mm/yr or greater.

Inyo fault zone—The northwest end of the Hunter Mountain fault merges with the Inyo fault zone in central Saline Valley west of the map area (Zellmer, 1980; Jennings, 1994; Oswald, 1998). This structure is entirely outside of the map area, but is discussed because of its importance to the larger fault system. This 20+ km-long fault zone (the western frontal fault of Zellmer, 1980) trends north-northwest along the western margin of the valley at the base of the steep topographic range front of the east-central Inyo Mountains. The fault zone is linked geometrically and kinematically with the Hunter Mountain fault zone in controlling the southwest-directed subsidence of the Saline Valley rhombochasm. The Inyo fault is a major normal-slip fault, as evidenced by the generation of the 3,000 m high east Inyo Mountain escarpment along its trace, with estimated 6,000 m of cumulative vertical displacement (Zellmer 1980), although there is evidence for some dextral slip along the zone as well (Oswald, 1998). Cichanski (2000) cites evidence for development of a basinward-sloping low-angle normal fault on at least one range-front facet that, like those on the western Panamint Range front to the south, are truncated at the range front by more recent high-angle scarps of the Inyo fault. Steep dips for the basin bounding faults in Saline Valley, including both the Inyo and Hunter Mountain faults, are supported by the narrow deep subsurface subbasin, with maximum depths exceeding > 3 km indicated by the gravity modeling of Blakely and others (1999). The eastern Inyo Mountain escarpment contains a pronounced suite of geomorphic features (for example, linear mountain-front-piedmont junction, large steep triangular facets, narrow incised wineglass canyons) indicative of high rates of vertical tectonic activity on the range-front fault. There are also numerous fault scarps of varying heights developed in Pleistocene and Holocene alluvial fans indicative of recurrent late Quaternary fault activity (Zellmer, 1980; Oswald, 1998; C.M. Menges and B. Turrin, unpublished mapping, 1983), with slip rates, although not directly determined, in the probable range of 1-3+ mm/yr.

Garlock Fault zone (southern section of the map area)

The structures and topography associated with the Eastern California basin and range abruptly terminate southward against the east-northeast-striking Garlock fault, a major left-lateral fault zone that can be traced 250 km eastward from its junction with the San Andreas fault to its apparent terminus at the western end of the Avawatz Mountains in southern Death Valley (Clark, 1973; Jennings, 1994). This fault separates the highly active strike-slip faults and associated basin-range structures of the eastern California basin and range from the less tectonically active pedimented terrane of the northern Mojave Desert to the south (Bull and McFadden, 1977; Jennings, 1994). Rowley (1998) describes the Garlock fault as a transverse zone, based on this sharp contrast in tectonic rates and styles across the fault following earlier suggestions that it is a province boundary or intracontinental transform by Hamilton and Myers (1966), Slemmons (1967), Davis and Burchfiel (1973), and Wernicke (1992).

The complex eastern end of the Garlock fault lies along the southwestern boundary of the map area. The main trace of the fault defines the northern boundary of the fault-controlled east-trending Pilot Knob Valley, which truncates the Slate Range, southern Panamint Valley, and the Owlshead Mountains on the south. The southern end of the Panamint Valley fault zone merges obliquely southeastward with this part of the Garlock fault in the Brown Mountain-Quail Mountains area. Also in this area, a large fault splay, the Owls Lake fault, trends to the northeast within a prominent strike valley in the central Owlshead Mountains. Complex deformation, manifested by mixed thrusts and right-lateral and left-lateral strike-slip faults, was observed in Wingate Wash between the Panamint and Owlshead Mountains by Pavlis and Serpa (1999), who relate this deformation to block rotations and translations along the eastern Garlock fault. Following a short gap, the Garlock zone projects to the east onto the complex multiple-strand Leach Lake fault zone in the narrow Leach Lake basin in the eastern Avawatz Mountains. In this area the Garlock fault zone converges with and terminates against the southeastern end of the southern Death Valley fault at the southern end of Death Valley to the north of the Avawatz Mountains. The structural junction between these two regional strike-slip fault systems results in significant local compression, as evidenced by the development of the Mule Springs thrust fault to the north of Leach Lake and the Avawatz Mountain thrust fault system further to the east. Both of these thrust systems displace late Tertiary and Quaternary sediments and surficial deposits and are responsible for the neotectonic uplift of the Avawatz Mountains (Jennings, 1994; Brady and Troxel, 1999).

There is abundant geomorphic and stratigraphic evidence, in the form of laterally offset or truncated landforms and fault scarps, for recurrent late Quaternary, and generally Holocene, displacements along the main fault trace and all of the subsidiary structures described above (Clark, 1973; Jennings, 1994). McGill and Sieh (1991) statistically analyzed suites of offset landforms along the main Garlock fault in Pilot Knob Valley to identify the two most recent surface ruptures with estimated average left-lateral displacements per event of 2-4 m. Estimates for slip rates on the Garlock vary from 2 to 11 mm/yr, with a preferred average of 7 mm/yr and recurrence intervals are generally interpreted between 200 and 3,000 yrs, depending on the fault segment (Petersen and Wesnousky, 1994). Total offset varies along strike of the Garlock fault zone and appears to die out to the east, within the map area where it intersects with the southern Death Valley fault zone.

Detachment Faults (throughout the map area)

Numerous low-angle fault surfaces with significant displacements have long been recognized within and along the flanks of the Panamint, Funeral, and Black Mountains. Many early workers considered these structures to be large thrust faults (Drewes, 1963; Hunt and Mabey, 1966). Wright and Troxel (1973, 1984) reinterpreted the low-angle faults as detachment faults related to large-scale regional extension. This extensional interpretation has persisted in various detachment models to the present, with such specific variants as rolling-hinge detachments, metamorphic core complexes, roll-over listric faults, and tilted-domino normal faults, in these and other areas of the eastern California basin and range (Hamilton, 1988; Holm and Wernicke, 1990; Wright and others, 1991; Topping, 1993; Burchfiel and others, 1987, 1995; Fridrich, 1999b; Wernicke, 1999; Snow and Lux, 1999; Cichanski, 2000). The mylonitic rocks of the turtleback surfaces in the Death Valley area are commonly interpreted as the uplifted and exhumed deep-crustal roots of normal faults related to this extensional deformation as well (Miller, 1999a). Many workers have proposed that the detachments and other low-angle normal faults have accomodated much, if not most, of the large amounts of regional extension observed across the eastern California region (Stewart, 1983; Hamilton, 1988;

Wernicke, Axen, and Snow, 1988; Wernicke and Snow, 1998; Wernicke, 1999; Niemi and others, 1999; Fridrich, 1999b; Snow and Lux, 1999).

The detachment faults are exposed within and along the flanks of the range blocks and involve primarily Tertiary or older rocks. These and other low-angle normal faults were certainly instrumental in the pre-5 Ma extensional deformation and related basin formation and volcanism in the region (Wright and others, 1991, 1999; Fridrich, 1999b; Snow and Lux, 1999). However, controversy exists regarding their relationship to the neotectonic structures that define the modern basin-range system described previously, and more fundamentally, whether the low-angle style of normal faulting they represent is a major element in the contemporary tectonics of the region. At one extreme, some workers propose that low-angle normal faults and detachments control modern extension and basin development (Burchfiel and others, 1987, 1995). A problem with this interpretation is evidence for cessation or waning of activity on many of the detachments themselves, as well as many strike-slip faults that appear kinematically related to them, and possibly the interrelated Black Mountain turtleback surfaces (Wright and others, 1999; Fridrich, 1999b; Miller, 1999a). In addition, many of the detachment faults and turtleback surfaces appear to be truncated at the range fronts by high-angle normal, oblique-normal, or strike-slip faults with abundant evidence for recurrent Pliocene to Quaternary activity (Keener and others, 1993; Miller, 1999b; Cichanski, 2000), although these observations may be accounted for in more than one fashion. Structural superposition of low-angle by high-angle normal faults is not only compatible with, but is predicted by, the rolling-hinge evolutionary model of detachment faults (Hamilton, 1988; Wernicke and Axen, 1988; Wernicke, 1992, 1999; Holm and others, 1992). Alternatively, the younger set of active faults within the basins and along the range fronts may represent development of a different neotectonic regime dominated not only by faults with steeper dips in at least the upper crust, but also including a significant component of right-lateral shear related to the eastern California shear zone (Cichanski, 2000). This observed shear component is not inherently accounted for in the basic rolling-hinge model by itself. The importance of high-angle structures with a significant lateral-slip component is also consistent with the steep-sided geometry of the many small sub-basins with pull-apart geometries that characterize the deep subsurface basin geometries evident in the gravity modeling of Blakely and others (1999).

LATE CALDERA MAGMATISM

Silent Canyon caldera complex (central section of the map area)

The Silent Canyon caldera complex is the oldest caldera complex identified so far in the southwest Nevada volcanic field. The complex underlies Pahute Mesa in the northwestern part of the NTS. The Grouse Canyon caldera of the Silent Canyon caldera complex was defined based mostly on geophysical methods because the caldera rim together with its intracaldera fill are everywhere buried by younger rocks, mostly ash-flow tuffs erupted from the adjoining Timber Mountain caldera complex. Because the caldera is filled with a very thick section of low-density ash-fall tuff, non-welded ash-flow tuff, and shard-rich sandstone, it gives rise to one of the largest isostatic gravity lows in Nevada. Gravity data together with data from deep exploratory drill holes indicate that the southern part of the Silent Canyon caldera complex may have been destroyed by the younger Timber Mountain caldera complex.

Caldera subsidence commenced with the eruption of the Tub Spring Formation of the Belted Range Group (Byers and Cummings, 1967; Byers and others, 1976b; Noble and others, 1968; Orkild, 1968; Orkild and others, 1968, 1969). The eastern rim of the resulting caldera (not shown on the map) is inferred to lie parallel to, but about 5 km farther to the east and northeast of the rim of the younger Grouse Canyon caldera. The Grouse Canyon Tuff of the Belted Range Group (Ar/Ar dates of 13.7 Ma) is the principal tuff derived from the complex according to the above-named authors and Warren and others (1998). It gave rise to what is now called the Grouse Canyon caldera (Sawyer and Sargent, 1989; Sawyer and others, 1994). Because of the great depth of the Silent Canyon caldera complex (greater than 3,600 m, based on drill-hole data; Sawyer and others, 1994), the possibility exists that other ash-flow sheets were erupted from the complex. Among these is the Bullfrog Tuff of the Crater Flat Group (13.25 Ma, Sawyer and others, 1994) as suggested by Byers and others (1976a). The Area 20 caldera (not shown on the map), inset into the Silent Canyon caldera complex, has been proposed as the source of the Bullfrog Tuff (Sawyer and Sargent, 1989; Sawyer and others, 1994). Drill holes on Pahute Mesa show at least 600 meters of Bullfrog Tuff ponded within the inferred caldera. Regardless of how many ash-flow sheets were erupted from the Silent Canyon complex, it obviously did not resurge.

Claim Canyon caldera (central section of the map area)

The Claim Canyon caldera (Christiansen and Lipman, 1965, Byers and others, 1976a, b) is a remnant of a large caldera that formed as a result of the eruptions of the Topopah Spring Tuff (12.8 Ma) and the Tiva Canyon Tuff (12.7 Ma), both formations of the Paintbrush Group. The bulk of the Claim Canyon caldera was destroyed by the younger Timber Mountain caldera complex. Only the southern margin of the Claim Canyon complex is exposed, and that margin has been interpreted as mostly a structural margin (Christiansen and Lipman, 1965). Most of the caldera has been resurgently domed (Sawyer and others, 1994).

Timber Mountain caldera complex (central section of the map area)

The Timber Mountain caldera complex as mapped by Carr and Quinlivan (1966), Christiansen and Lipman (1965), Byers and Cummings (1967), Lipman and others (1966), O'Conner and others (1966), Hinrichs and others (1967), Orkild and O'Conner (1970), and Byers and others (1976a) and described in detail by Byers and others (1976b) and Christiansen and others (1965, 1977) consists of the Rainier Mesa caldera that formed as a result of the eruption of the Rainier Mesa Tuff of the Timber Mountain Group at 11.6 Ma, and the Ammonia Tanks caldera that formed as a result of eruption of the Ammonia Tanks Tuff of the Timber Mountain Group at 11.45 Ma (Sawyer and others, 1994). Other rhyolite tuffs and lavas of limited distribution that are part of the Timber Mountain Group were also erupted from the caldera complex. The complex is centered around Timber Mountain, which formed as a result of the resurgence of the Ammonia Tanks caldera (Carr and Quinlivan, 1966). The topographic margin of the Rainier Mesa caldera, about 35 km in longest diameter, is clearly exposed in many places. The Ammonia Tanks caldera is nested entirely within the Rainier Mesa caldera.

The structural margin of the Ammonia Tanks caldera, with a largest diameter of nearly 20 km, is exposed on the eastern margin of Timber Mountain and inferred elsewhere around it. Neither the structural margin of the Rainier Mesa caldera nor the topographic margin of the Ammonia Tanks caldera is exposed, but these margins, as well as unexposed parts of the topographic margin of the Rainier Mesa caldera and the structural margin of the Ammonia Tanks caldera, are inferred from geophysical studies by Grauch and others (1997), Ponce (2000), Ponce and others (2000), Hildenbrand and others (1999), Mankinen and others (1999), McKee and others (1999), and Schenkel and others (1999), and from geologic studies (Slate and others, 2000). A miniature caldera, the Twisted Canyon caldera, located about 15 km southwest of the Timber Mountain complex, resulted from the eruption of ash-flow tuff of the rhyolite of Twisted Canyon. This rhyolite is included in the Timber Mountain Group on the basis of its lithology and its age between the Rainier Mesa and the Ammonia Tanks, despite the fact that it is well removed from the Timber Mountain caldera complex (Fridrich, 1999a; Fridrich and others, 1999b).

Black Mountain caldera (central section of the map area)

The Black Mountain caldera, located northwest of the Timber Mountain complex, erupted peralkaline ash-flow tuff, lava flows, and nonwelded tuff between 9.4 and 9.15 Ma (Vogel and others, 1989; Sawyer and others, 1994). The two major ash-flow tuff cooling units are the Pahute Mesa and Trail Ridge Tuffs of the Thirsty Canyon Group. Both of these tuff units mantle broad areas in the northwestern NTS. Several other tuffs of limited distribution also were erupted from the caldera. The caldera was mapped by Christiansen and Noble (1968) and Noble and Christiansen (1968), and it was described by Noble and others (1964, 1984). Although the caldera margin is in most places covered by younger volcanic units, the location of the topographic margin can be inferred accurately (Noble and others, 1984).

Stonewall Mountain caldera (northwestern section of the map area)

Stonewall Mountain is a nearly circular, 14.5-km-diameter massif, first recognized as a volcanic feature by Spurr (1902), that rises abruptly 620 m above Stonewall Flat. The Stonewall Flat Tuff consists of the Spearhead Member (Spearhead Rhyolite of Ransome and others, 1910) and the overlying Civet Cat Canyon Member of Noble and others (1984) with ages of approximately 7.6 to 7.5 Ma (Hausback and others, 1990; Sawyer and others, 1994; Slate and others, 2000). These two ash-flow sheets have been associated with episodes of caldera subsidence that were previously assigned to the Thirsty Canyon Tuff of Black Mountain (Ekren and others, 197l; Noble and others, 1964; Christiansen and Noble, 1965). Stonewall Mountain is composed mostly of intracaldera tuff of the Civet Cat Canyon Member. Blocks of lower Paleozoic sedimentary rocks present on the resurged mountain suggest that the caldera related to the extrusion of the Civet Cat Canyon Member may have resurged in its entirety, including parts of the floor.

Noble and others (1984) and Weiss and Noble (1989) concluded that the caldera related to the extrusion of the Spearhead Member was considerably larger than the diameter of Stonewall Mountain, and that only a part of the caldera resurged. However, Hausback and Frizzell (1986) reinterpreted the depression southeast of Stonewall Mountain as a small caldera. They considered that it resulted from the extrusion of the

Civet Cat Canyon Member. More likely, it formed as a result of extrusion of the Spearhead Member, and did not resurge.

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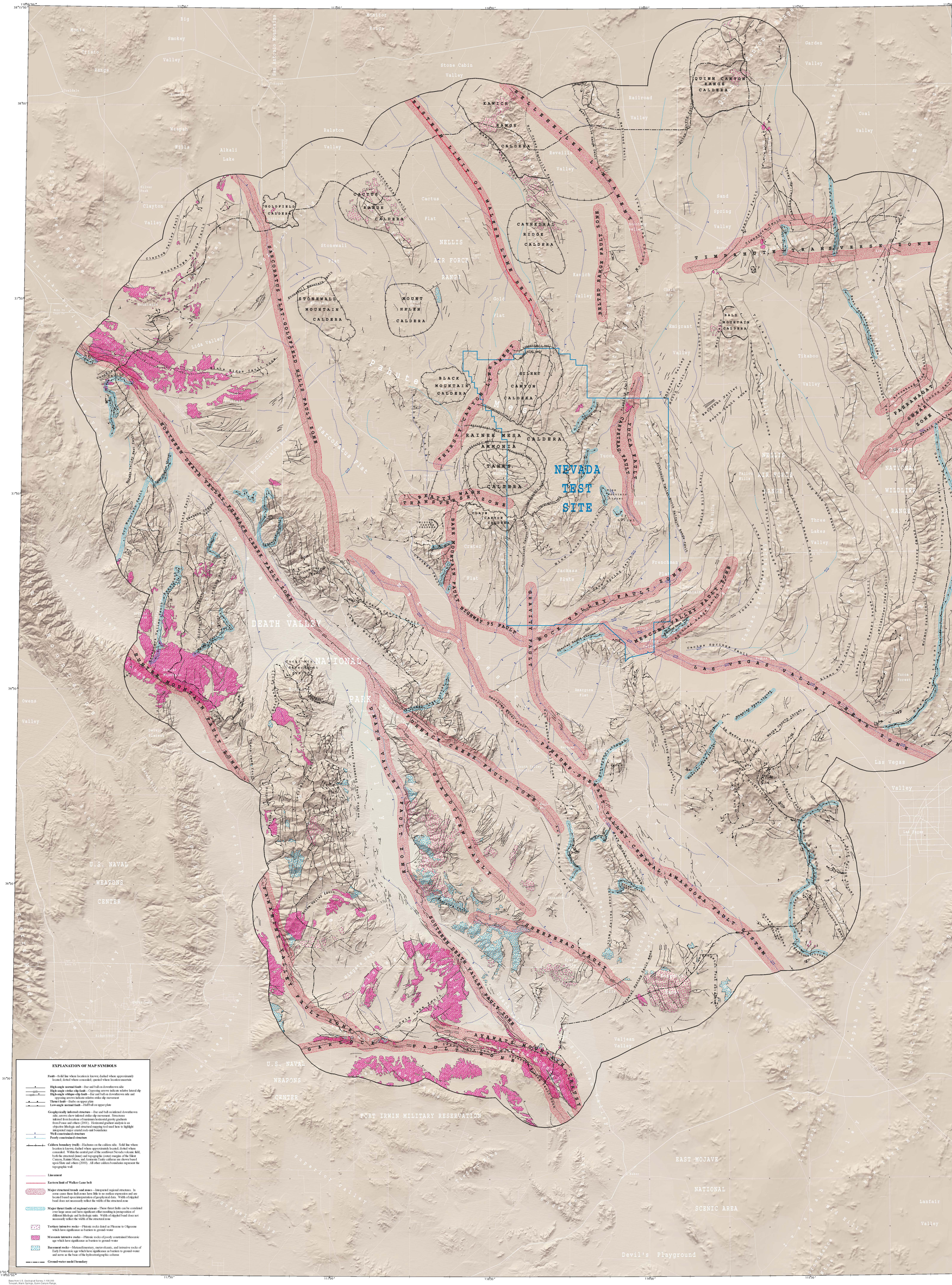
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
NEVADA OPERATIONS OFFICE, NATIONAL NUCLEAR SECURITY ADMINISTRATION,
U.S. DEPARTMENT OF ENERGY (INTERAGENCY AGREEMENT DE-A108-96NV11967)

MISCELLANEOUS FIELD STUDIES MAP MF-2381-B
Version 1.0
Pamphlet accompanies map



Base from U.S. Geological Survey, 1:100,000 Tonopah, Warm Springs, Quinn Canyon Range, Goldfield, Cactus Flat, Timpahute Range, Last Chance Range, Pahute Mesa, Pahranagat Range, Saline Valley, Beatty, Indian Springs, Darwin Hills, Death Valley Junction, Las Vegas, Ridgecrest, Owlshead Mountains, Mesquite Lake, Cuddeback Lake, Soda Mountains, and Ivanpah DLG and DEM data, 1999.
Projection and 10,000-meter grid, zone 11 Universal Transverse Mercator
25,000-foot ticks based on California coordinate system, zones 4 and 5 and Nevada coordinate system, east, west, and central zones.
1927 North American Datum

SCALE 1:250 000

5 0 5 10 15 20 MILES

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TECTONIC MAP OF THE DEATH VALLEY GROUND-WATER MODEL AREA, NEVADA AND CALIFORNIA

By
J.B. Workman, C.M. Menges, W.R. Page, E.B. Ekren, P.D. Rowley, and G.L. Dixon
2002

This map was produced on request, directly from digital files, on an electronic plotter

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